This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

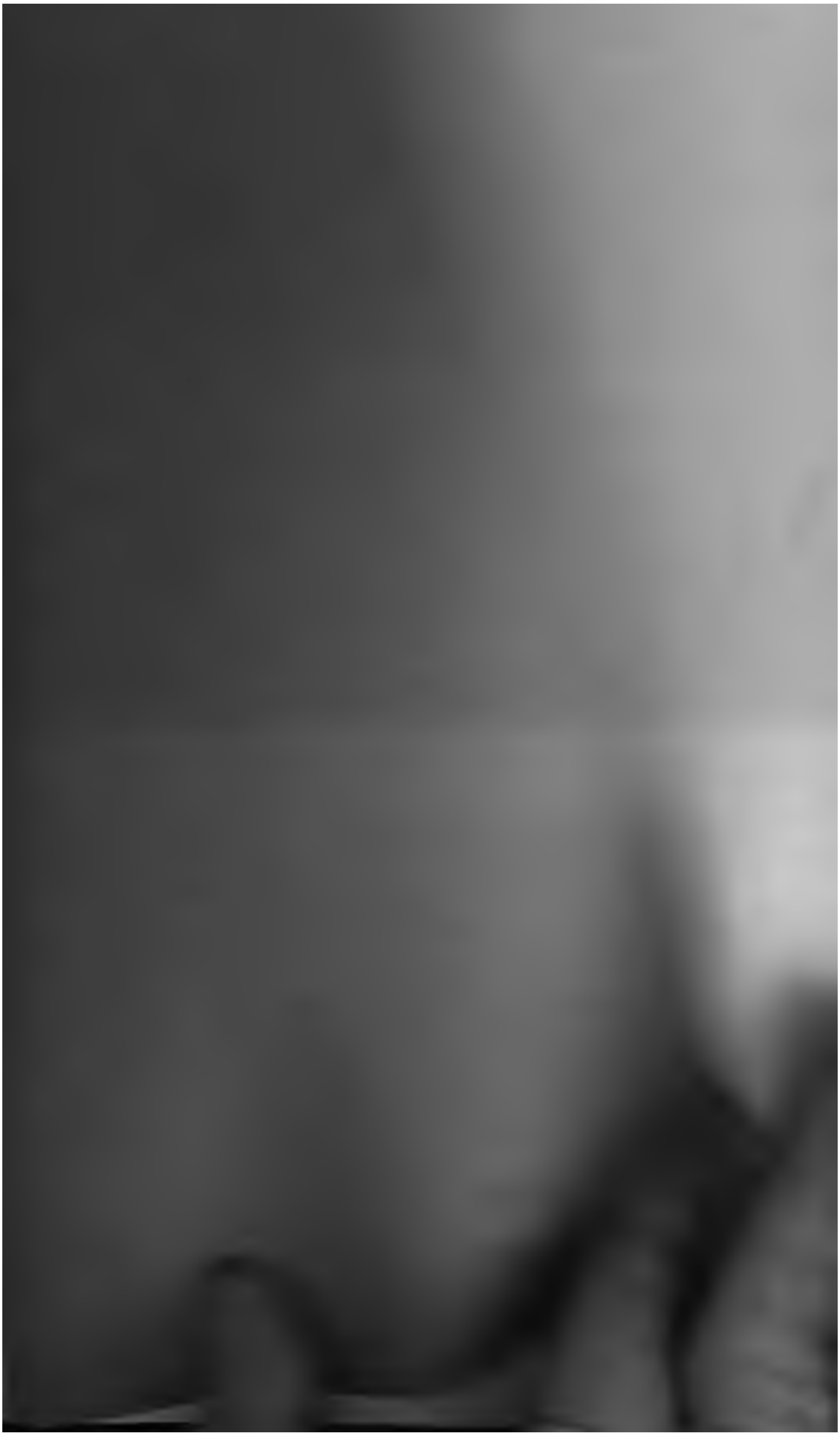
We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.
+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.
+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.
+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

3 3433 06641915 5



PVI

The
Geology and Scenery of the Grampians
and
The Valley of Strathmore

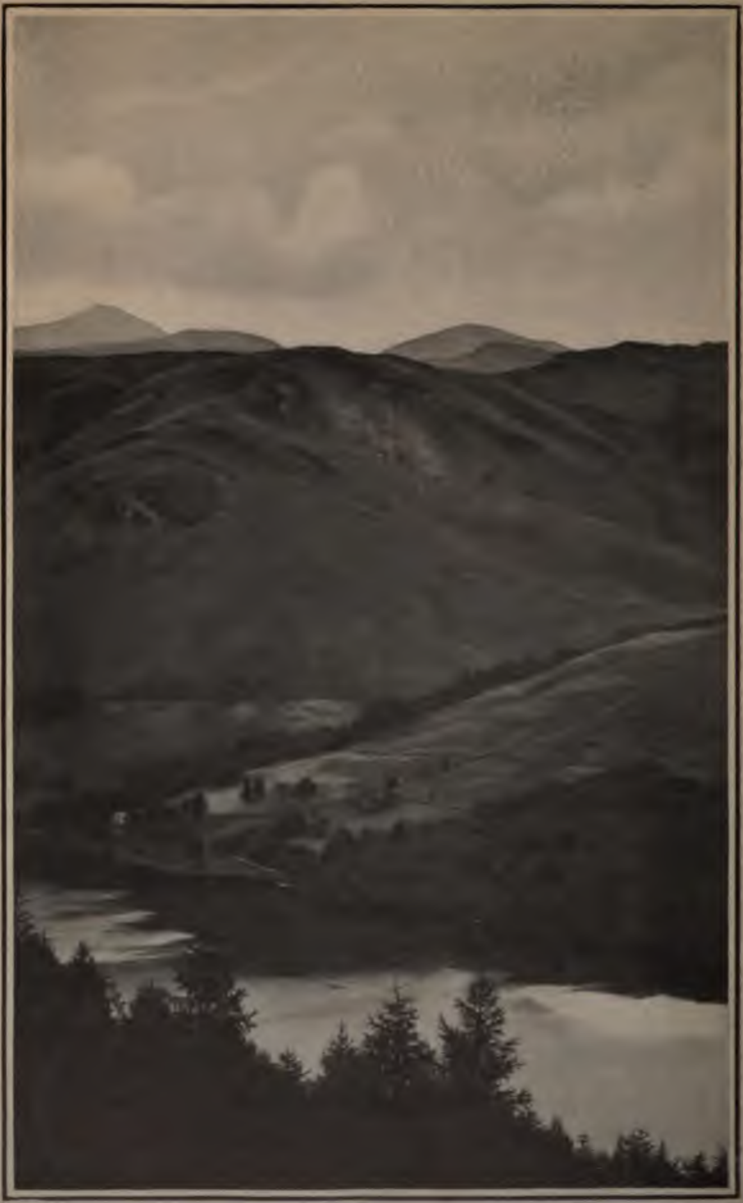
Volume I

GLASGOW
PRINTED AT THE UNIVERSITY PRESS BY
ROBERT MACLEHOSE & COMPANY LTD. FOR
JAMES MACLEHOSE AND SONS, PUBLISHERS
TO THE UNIVERSITY OF GLASGOW

MACMILLAN AND CO. LTD.	LONDON
THE MACMILLAN CO.	NEW YORK
MACMILLAN CO. OF CANADA	TORONTO
SIMPKIN, HAMILTON AND CO.	LONDON
BOWES AND BOWES	CAMBRIDGE
DOUGLAS AND FOULIS	EDINBURGH

MCMVIII

*This Edition is limited to Four Hundred and
eighty copies for sale.*



Stobinian (3827 ft.) and Ben More (3843 ft.), from Dun Mhor, Loch Voil, showing Highland Plain of Marine Denudation and results of Glaciation

Photo. by A. S. Reid, M.A., F.G.S.

The Geology and Scenery of the Grampians

and

The Valley of Strathmore

By

Peter Macnair, F.R.S.E., F.G.S.
Curator of the Natural History Collections in the Glasgow Museums
Lecturer on Mineralogy and Geology in the Glasgow and
West of Scotland Technical College
Examiner in Geology in the University of Aberdeen
Honorary Secretary of the Geological Society of Glasgow

Illustrated with numerous Photographs, Diagrams and Maps

VOLUME I

Glasgow
James MacLehose and Sons
Publishers to the University
1908

THE NEW YORK
PUBLIC LIBRARY
670591
ASTOR, LENOX AND
TILDEN FOUNDATIONS
R 1914 L

PREFACE

The object of this work is to present a summary of the geological structure of the Grampians and the great Valley of Strathmore. These two important divisions of Scotland lie respectively to the north-west and south-east of the Highland boundary fault. This great fault can be traced through Arran and Bute, crossing to the mainland near Toward Castle, from which point it can be followed across the whole of Scotland by Balmaha, Aberfoyle, Callander, and Dunkeld, to the sea at Stonehaven. Geographically, this line divides the Highlands from the Midland Valley; and geologically, the crystalline schists of the Grampians from the Old Red Sandstone rocks of the broad Valley of Strathmore.

These two formations, as they are developed in the counties of Perth, Stirling, Dumbarton, and Argyll, and along the shores of the Firth of Clyde, present many interesting features in structural and dynamical geology. Thus, in the Grampians we have the basal wreck of what was at one time a great mountain chain, such as the Alps, but which has now been laid bare to its very core by the scalpel of denudation—so affording to the student of geology a glimpse into the complex processes of mountain building. The broad Valley of Strathmore, from Loch Lomond to the sea at Stonehaven, is paved with a vast thickness of Old Red Sandstone rocks, and is bounded on its south-eastern side by the thick piles of volcanic material forming the Sidlaw and Ochil Hills. The physical conditions under which the conglomerates and sandstones of the Scottish Old Red Sandstone were accumulated, has been the subject of much controversy, and this most interesting problem in Scottish geology has been dealt with in considerable detail. Much of the finest scenery of Scotland lies within the area embraced in the title of this book, and it has afforded numerous striking examples of the intimate relationships that exist between the geological structure and scenery of a country.

I have made a special study of this area, which has extended over a considerable period of time, and the work, while it expounds many of the well-known principles of Scottish geology, also contains the results of a considerable amount of original research, bearing upon the structure of the Grampians and the physical conditions under which the later Palaeozoic rocks were accumulated.

I have to express my great indebtedness to Mr. H. Coates, Perth, for much assistance in the production of this book, my thanks being especially due to him for a large number of the photographs which enrich the volume, and for the diagram showing the gradient of the Tay Valley from its source to the sea. My best thanks are also due to a large number of friends who have kindly given permission to reproduce their photographs. These include Mr. A. S. Reid, M.A., F.G.S., Trinity College, Glenalmond; Mr. W. Lamond Howie, F.C.S., Harrow; Dr. R. Kidston, F.R.S., F.G.S., Stirling; Mr. James W. Reoch, Mr. Samuel Fingland, and Mr. Charles Kirk, Glasgow; Mr. James Richardson and Mr. W. D. M. Falconer, Blairgowrie; Mr. D. M. Gall, B.Sc., Crieff; Mr. G. F. Bates, B.A., B.Sc., Mr. S. Ellison, Mr. J. S. Grant, Mr. Alex. M'Kenzie, Mr. Wm. Reid, Perth; and Mr. John Stuart, Helensburgh.

I am also indebted to Mr. John Ritchie, LL.B., Perth, for permission to reproduce his diagrammatic chart of the hills seen from Corsiehill, Perth; to Professor James W. H. Traill, LL.D., F.R.S., Aberdeen, for permission to reproduce a photograph from his miniature of Professor Nicol; to the Glasgow Corporation for permission to reproduce the medallion of James Hutton, by Tassie, in the Kelvingrove Museum; to the Trustees of the British Museum for permission to reproduce a photograph of *Holoptychius nobilissimus* from Clashbennie, and to the Managers of the Public Museums, Dundee, for permission to reproduce a photograph of *Pterygotus anglicus*.

The chapter dealing with the physical conditions under which the Old Red Sandstone has been accumulated was in great part originally contributed to the *Geological Magazine* by Mr. James Reid and myself, and I have to acknowledge my indebtedness to him for the kind manner in which he has permitted me to reprint it in this work.

Finally, I have to tender my warmest thanks to Mr. James W. Reoch for his great assistance in reading the proofs and in seeing the work through the press.

P. MACNAIR.

GLASGOW, *April*, 1908.

CONTENTS

PAGE

CHAPTER I

THE CYCLE OF DESTRUCTION AND REPRODUCTION - 1

CHAPTER II

HISTORICAL INTRODUCTION - - - - - - 24

CHAPTER III

OUTLINE OF THE PHYSIOGRAPHY AND GEOLOGY OF THE GRAMPIANS AND STRATHMORE - - - 60

CHAPTER IV

THE METAMORPHIC ROCKS OF THE GRAMPIANS
1. Rocks of Sedimentary Origin - - - 87

CHAPTER V

THE METAMORPHIC ROCKS OF THE GRAMPIANS
2. Rocks of Igneous Origin - - - - 128

CHAPTER VI

THE GEOLOGICAL STRUCTURE OF THE GRAMPIANS - 149

CHAPTER VII

THE ROCKS OF THE HIGHLAND BORDER, OR MARGINAL BELT - - - - - - - - 184

LIST OF ILLUSTRATIONS

VOLUME I

Stobinian (3827 ft.) and Ben More (3843 ft.) from Dun Mhor, Loch Voil, showing Highland Plain of Marine Denudation, and Glaciation - - *Frontispiece*

FIG. PAGE

1. Dyke of Igneous Rock intruded into Sandstones at Dalcrue Bridge, Almondbank - - - - 12
2. Portrait of James Hutton - - - - - - - 16
3. View from Ben Ghlas, looking to Killin, Glen Dochart, and Ben More - - - - - - - - 20
4. Ben Lawers, from the summit of Ben Ghlas - - - 22
5. Portrait of James Nicol - - - - - - - 32
6. View from the summit of Ben Lawers along the great Axial line of Folding - - - - - - - 48
7. Ben Laoigh, from Coninish (the source of the Tay) - 66
8. Looking up Strathfillan to Ben Laoigh, from north side of Ben More - - - - - - - - 68
9. The Killin Hills from the Dochart - - - - 70
10. Lower Falls of Moness, near Aberfeldy - - - 72
11. Falls of Balnaguard, near Logierait - - - - 74
12. On the line of the Boundary Fault, Craigie Barns, Dunkeld - - - - - - - - 76
13. Strain-slip in Folded Ben Ledi Grits, Ben Ledi - - 90
14. Clay Slate, Pass of Leny. (Magnified 40 dias.) - - 92

FIG. PAGE

15. Craiglea Quarry, showing Stratification and Cleavage of Clay Slate - 96

16. Cleavage, Stratification, and Reversed Fault, in Clay Slate 100

17. Ben Ledi Grit, Ben Ledi. (Magnified 40 dias.) - 104

18. Ben Ledi Grit, Ben Ledi. (Magnified 25 dias. Crossed Nicols) - 106

19. Epidote-Schist (Green Beds), Loch Katrine. (Magnified 40 dias.) - 108

20. Limestone, Loch Tay. (Magnified 25 dias.) - 110

21. Folded Limestone, Glenample, Lochearnhead - 112

22. Garnetiferous Mica-Schist, Aberfeldy - 114

23. Garnetiferous Mica-Schist. (Magnified 40 dias. Crossed Nicols) - 116

24. Greywacke, with Hornblende, Creag na Caillich. (Magnified 40 dias.) - 118

25. Ben Lawers Phyllite, Creag na Caillich. (Magnified 40 dias.) - 120

26. Ben Lawers Phyllite, showing Strain-slip, Ben Lawers - 120

27. Ben Lawers Phyllite, Ben Lawers - 122

28. Folded Ben Lawers Phyllite, at summit of Ben Lawers - 124

29. Quartzite, Falls of Tummel. (Magnified 25 dias.) - 126

30. Balhoulan Quarry, Pitlochry, showing Hornblende-Schist, with vein of Pegmatite - 128

31. Folded Hornblende-Schist in Balhoulan Quarry, Pitlochry 130

32. Banded Hornblende-Schist, Creag na Caillich - 132

33. Banded Hornblende-Schist, with Reversed Faults, Pitlochry - 134

34. Epidiorite, Creag na Caillich. (Magnified 40 dias.) - 136

35. Hornblende-Schist, Loch Tay. (Magnified 40 dias.) - 140

36. Serpentine, Corrycharmaig. (Magnified 25 dias. Crossed Nicols) - 142

FIG. PAGE
37. Diagram section through Ben Vrackie, showing Sill of Hornblende-Schist - - - - - - - 144
38. Pass of Killiecrankie, and Ben-y-Ghloe - - - 148
39. Diagram to illustrate the formation of the Grampian Geosynclinal and Geanticlinal - - - - 151
40. View from the Summit of Ben Lawers, looking North-East along the great Axial line of Folding - - 152
41. Diagram to show the different parts of a Fold - - 153
42. Diagram to illustrate overfolding, and the production of Reversed Faults - - - - - - - - 155
43. Diagram to show the structure of highly-folded areas - 158
44. Five Horizontal Sections to illustrate the Structure of the Highlands - - - - - - - - - 160
45. Deformed crystal of Pyrites, from the Ben Lawers Phyllite, Creag na Caillich, Killin - - - - 160
46. Outcrop of Folded Loch Tay Limestone, showing direction of over-folding, Druim na Lairig, Killin - - 164
47. Outcrop of Folded Loch Tay Limestone. Head of Glen Ogle - - - - - - - - - - 166
48. Creag na Caillich, Killin, from the Lochay - - - 168
49. View of Ben Lawers and Ben Ghlas, from Killin - - 170
50. Ben Doireann, from the South - - - - - - 172
51. Diagrammatic Section across Ben Ledi, to show its Geological Structure - - - - - - - 175
52. Diagrammatic Section across Ben Venue, to show its Geological Structure - - - - - - - 177
53. Ben Venue, from the Trossachs - - - - - 178
54. Section across Meall Uaine, near Pitlochry - - - 181
55. Loch Katrine, with Ellen's Isle and Ben A'an, from the summit of Ben Venue - - - - - - - 182
56. View along the Marginal Belt, with Ben Ledi in the distance - - - - - - - - - 184

FIG. PAGE
57. Diagram Section across Kilmahog Quarry, near Callander 187
58. Lime Hill, on the Marginal Belt, near Aberfoyle - - 188
59. Section across the rocks of the Marginal Belt - - 191
60. Section across the rocks of the Marginal Belt - - 191
61. Folded Cherts in Corrie Burn, west of Aberfoyle - - 192
62. Section across the Marginal Belt in Kincardineshire (after Barrow) - - - - - - - - - 193
63. The Menteith Hills, from the west of Aberfoyle - - 194

COLOURED AND FOLDED MAPS AND DIAGRAMS

The Grampians as seen from Corsiehill, Perth - *facing page* 60
Diagram to show the Gradient of the Tay Valley from the source to the sea - - - - - - - - 64
Geological Sketch Map of the District round Killin - - 138
Geological Sketch Map of the District round Ben Vuroch 144
Sketch Map and Sections, showing the Structure of the Loch Tay District - - - - - - - - - 162
Geological Sketch Map showing the rocks of the Marginal Belt - - - - - - - - - - 186
Geological Sketch Map to illustrate the Structure of the Highlands - - - - - - - - - 196

CHAPTER I

THE CYCLE OF DESTRUCTION AND REPRODUCTION

> The earth never tires,
> The earth is rude, silent, incomprehensible at first,
> Nature is rude and incomprehensible at first.
> Be not discouraged, keep on, there are divine things well envelop'd,
> I swear to you there are divine things more beautiful than words can tell.
>
> WHITMAN.

WE are so accustomed to look upon the mountains, the hills, and the solid land, as the only permanent elements in the scenery that surrounds us, that we attribute to them an eternal existence, and speak of them as the everlasting hills. But with a rude hand the science of geology has drawn aside the veil of mystery that hung heavy and deep across the mountains, and has shown us that they are not eternal, they are not primeval, but are only the offspring of time.

Geology in its widest interpretation is that department of natural science which deals with the past history of the earth as it is recorded in the rocks. It tells of those vast cycles of change, which the crust of the earth has been continually undergoing since the beginning. The remains of animals and plants which we find in the rocks are perhaps our surest guides in interpreting these changes; but they can only be regarded as part of the evidence, for we find that in the very oldest rocks we have to rely mainly upon the evidence of great physical masses, which, though entirely devoid of organic remains, constitute the only records of the earlier chapters in the history of our earth.

The geologist, then, has to examine the various rocks that enter into the crust of the earth; he has to explain their appearance, structure, form, mode of occurrence, relative position, age and distribution, and, by a consideration of all these characters, arrive at some conclusion as to their origin and history. He has also to inquire into the animal and vegetable contents of these rocks, and to explain how they have become entombed in their rocky sepulchres. By comparing these fossil animals and plants with living forms he attempts to arrive at some conclusion regarding their structure and habits.

In a word, the science of geology may simply be considered as an attempt to reconstruct the past physiographical conditions through which the earth has successively passed. It pictures the former distribution of land and sea; it tells of continents that have long since vanished, and of scenery and inhabitants that have passed away. It has to do with the ancient botany, zoology, and geography of the globe, and, in seeking to write the history of these, it interprets the past by those laws which are at present seen in operation upon the earth, and which have been invariable and universal throughout all geological time.

Most of my readers have doubtless stood upon the sea-shore during a storm and watched the billows as they came surging against a rocky cliff; and if they had carefully considered the action of the waves, and then examined the characteristic features of the cliff along the sea-shore they could not fail to be impressed with the extensive amount of disintegration which is being carried on by the sea.

Where the rocks are comparatively soft they are worn away much more rapidly than where they are of a harder and more massive character: thus rocks formed of soft clays and muds are more easily eroded than sandstones or granites; but in the course of time even the hardest of rocks become broken up by the assaults of the ocean, and so become worn more and more backwards.

When the cliffs rise into rocky precipices the material which is derived from the breaking up of the rocks usually forms heaps of shingle along the base of the cliffs; these are acted upon by the waves, which roll them incessantly backwards and forwards, and when the sea is lashed with a storm they are lifted and hurled against the cliffs as with the action of some mighty artillery. A wave itself appears to have little or no grinding power, but when it is charged with gravel, boulders, and large blocks of stone, it becomes a most formidable instrument in the destruction of solid land.

Most rocks are traversed by joints or fissures, and the air finding its way into these fissures at ordinary atmospheric pressure is sometimes forced through by the rush of the waves, and escapes on the landward side, thus forming blow-holes. If the air does not escape it remains in the crevice or fissure. An operation analogous to blasting occurs. For a moment the waves and air pressures balance one another, then as the waves recede, the compressed air, finding no means of escape, suddenly expands like an explosive charge, thus further widening the fissures and breaking off pieces of the rock.

Again, as the sea erodes the coast line along its base, gravitation comes into play on the overhanging cliffs, and landslips and rock-falls are frequent, especially if the rocks dip towards the sea.

The denuding action of the sea tends to reduce the land to a dead level, and in the course of ages a great continent may be levelled down by the action of the waves, forming what is called by geologists a plain of marine denudation. If we ascend the high ground which rises behind the town of Greenock and look northwards across the Firth of Clyde to the Highland hills, the first thing that will strike us is the almost dead uniformity of level to which they rise ; there is no outstanding peak, or series of peaks, which dominates the rest. In fact, if we were to take a straight-edge and place it against the mountain summits, we would find that it was practically level. The only agents that geologists are acquainted with, which could have produced such a great plain, are atmospheric denudation aided by sea waves upon the cliffs of the sea-shore. In a future chapter we shall see that the rocks which form the Scottish Highlands have been bent and folded to an enormous extent, and that at an early period in their history they must have formed a true mountain chain of elevation. But the most superficial study of the topographical features and geological structure of the Highland hills shows that the mountains and valleys of this ancient continent must have been reduced to a base level of erosion beneath the surface of the ocean. (See Frontispiece.)

If we now betake ourselves to the summit of such a mountain peak as Goatfell in Arran, we shall see that here also a slow, but sure, process of rock destruction is being silently, but continually, carried on. Particle by particle, grain by grain, the solid granite of the mountain is being disintegrated, carried into the nearest rivulet, and from the rivulet into the stream, which hurries it downwards and ultimately deposits it in the bed of the ocean.

Let us now examine this process of destruction a little more carefully. And for this purpose it will be necessary that we should briefly inquire in the first place into the mineralogical structure and composition of a piece of granite of which the mountain is formed. Most granites consist essentially of three minerals—quartz, felspar, and mica—and the rock presents a thoroughly crystalline structure, by which is meant that it has no glassy base, or matrix, such as is seen to be present in certain other rocks. The quartz can be easily recognized by its clear glassy appearance, and by its superior hardness, as it cannot be scratched with a knife. The felspar may be either red, grey, or yellow in colour. It can be distinguished from the quartz by not being transparent, by being less hard, so that it can be scratched with a knife, and also by the manner in which it tends to break along certain definite directions called lines of cleavage. The mica may be either white, brown, or black in colour, and occurs in well-developed crystals, which are usually six-sided in shape. The mica has a tendency to break into thin plates or films, which is one of its most characteristic features. This property is the same as that already referred to as occurring in the felspar, and is known as cleavage.

These three minerals are known as the essential minerals of granite, by which it is understood that they must all exist in the rock in a fair proportion before it can be called a true granite.

The great agents in the disintegration of granite are rain and water flowing over its surface. When water charged with carbonic acid is allowed to act upon a mass of granite the first mineral to be attacked and decomposed is the felspar, which is composed practically of silicate of potash. The carbonic acid decomposes this silicate of potash with the formation of a soluble compound, carbonate of potash, and an insoluble compound, silica, which is easily washed away. When the felspar is decomposed and washed away, the coherency of the different minerals in the granite is much impaired, and the rock becomes disintegrated, the mica and quartz being broken down into small pieces.

Once the granite has become broken down gravitation comes into play with more effect, and being assisted by rain and snow, the granite, or rather what remains of it, is washed down the hillsides by the rivulets into the rivers, and finally into the sea. The finer argillaceous matter that has been derived from the felspar, being light and flocculent, is washed down as mud and deposited further out in the ocean.

Rivers tend to erode their valleys, thus conveying fragments of the country over which they pass to the sea. A river in its upper reaches flows so rapidly that it has no time to accumulate sediment; its work of transport therefore begins after the mountain torrent has settled down to a more smoothly running stream.

The chief manner in which a river transports waste matter is by rolling stones along its bed, thus rounding the fragments broken off cliffs and scars. These stones gradually, and in a long space of geological time, become worn down, and form shingle banks along the bed of the stream, and finally along the sea-shore. Rivers also carry much matter in suspension; fragments too light to sink to the bottom are transported in this manner. These small fragments are usually pieces chipped off the over-hanging rocks by frost, or by the alternation of heat and cold; thus frost acts on rocks, by the rain entering through minute cracks and fissures, or by soaking into the rocks, almost all rocks being more or less porous. When the water freezes, it expands and exerts great breaking force; fissures are thus formed, which each succeeding frost widens, until the surface of the rock breaks off in fragments.

The term *sub-aerial denudation* is used to express the changes which are being brought about by atmospheric agencies in wearing away the surface of the earth, and includes the action of frost, which bursts the rocks asunder; rain, which acts both chemically and mechanically upon the rocks, disintegrating and carrying the particles into the rivers; wind, which wears down sand grains, and the rocks against which it drives them; and chemical action, which dissolves certain constituents of the rocks, allowing the others to crumble away. On the other hand, the term *marine denudation* is used to describe the action of the sea in breaking up and destroying the solid land. Together these two great agents of change are continually at work, and, if there were no counteracting agents, in the course of time the solid land would eventually disappear and a shoreless ocean would encircle the globe, or as Swinburne has so vividly put it:

> "Till the slow sea rise and the sheer cliff crumble,
> Till terrace and meadow the deep gulfs drink,
> Till the strength of the waves of the high tides humble
> The fields that lessen, the rocks that shrink,
> Here now in his triumph where all things falter,
> Stretched out on the spoils that his own hand spread,
> As a god self-slain on his own strange altar
> Death lies dead."

That this process of destruction and reproduction of the solid land has been going on for countless ages is made abundantly clear by a study of the solid crust of the earth, every cliff and quarry bearing witness to some phase or other in this great cycle of change.

If we enter a sandstone quarry such as may be seen in many parts of our country, and which is now far removed from the neighbourhood of the sea, the first thing that arrests our attention is the regular stratification of the rocks, which indicates that they have been deposited by aqueous action. One layer is seen to succeed and rest regularly upon the other, though occasional irregularities are to be met with, showing the effect of currents in the sea. Ripple-markings, sun-cracks, rain-prints, and the presence of the remains of fossil animals in the strata, all point to the aqueous origin of such a rock. The remains of animals that lived in the sea and of plants that lived upon the land, when the sandstone was being accumulated, have been preserved in these rocks in several ways. Thus nothing may have been left behind but a simple impression of the plant or animal. This kind of fossil is well exemplified in the remains of fossil ferns that are often found in the Carboniferous rocks. Secondly, the plant or animal may have been replaced by a more or less perfect cast made in sand, mud, or lime. In this method the external shape of the fossil may have been most perfectly preserved though its internal structure has become entirely obliterated. In the third method of fossilization, when the plant or animal began to decay, each particle of organic material was replaced by a particle of chemical matter, such as silica, or carbonate of lime, and in this manner its most minute microscopical structure has often been beautifully preserved. This process of fossilization is usually best seen in vegetable remains.

Sandstone, then, is merely a mass of consolidated sand. That it is an aqueous rock is shown by its composition and structure. The microscope reveals it to be made up of small fragments of quartz and mica which have been broken down and worn until they have assumed a rounded shape. Such rocks as are seen in a sandstone quarry have been hardened in several ways, chief amongst these being pressure, heat, and chemical action. The superincumbent layers of material exert pressure on the lower layers, and so consolidate the rock-forming materials. It has been estimated that a thousand feet of strata will exert a pressure of half a ton per square inch on the underlying material.

The infiltration of water containing carbonate of lime, magnesia, or iron, with deposition of these carbonates amongst the loosely lying grains or pellicles, will bind the whole into a firm, compact rock.

The great series of sedimentary or fragmental rocks include all those that, like sandstone, have had a secondary, or derivative, origin; or, in other words, they have been formed out of previously existing materials. Some of these have been formed by the action of the wind along the sea-coast, such as sand dunes. Others owe their origin to moving water, and under this category may be included the gravel, sand, and mud of shores and river beds. Still another group has been formed by the slow accumulation of the remains of plants and animals which formerly existed upon the surface of the earth and in lakes or seas. Coal and limestone are familiar examples of this class of rocks; they are known as organically formed rocks. The loose *debris* which is ejected from the mouths of volcanoes may fall either upon the surface of land or upon the sea, and by slow accumulation fragmental rocks of volcanic origin are formed. These are known as volcanic tuffs or agglomerates.

From what has been said it will be seen that, in dealing with the different kinds of detrital rocks, their degree of consolidation is not of much importance. Sand and mud accumulated at the bottom of a modern sea or lake bottom differ in no essential respect from ancient sandstones and shales, and both may tell their geological story equally well. It is impossible to draw any line of demarcation between what is popularly called rock, and the loose detritus which at some future period may pass into a solid condition.

Besides these fragmental rocks, which form by far the larger proportion of the rocks exposed at the surface of the earth, there is another great class known as igneous rocks, which have resulted from the consolidation of molten material formed in the interior of the earth. There is good reason for believing that the temperature of the earth's interior is sufficiently high to melt any rock which we know to exist upon its surface. It seems most likely, however, that this liquefaction will be held in check by the enormous pressure which must exist so far beneath the surface. When an eruption of molten material takes place the pressure is relieved and the liquid rock finds its way along the line of least resistance.

The classification of the igneous rocks is usually based either upon their mode of occurrence or upon their chemical composition. When the former principle is used they are divided into volcanic and plutonic, or, as they are sometimes called, extrusive and intrusive rocks.

The volcanic or extrusive rocks have been ejected upon the surface of the earth by volcanic action, and have been laid down either as great sheets of lava or as accumulations of fragments of lava. In some instances these lavas have cooled suddenly, when they present a glassy, or only partly crystalline, structure. In other cases they have cooled more slowly and have become entirely crystalline, though the crystals are usually very minute.

On the other hand, plutonic or intrusive rocks have cooled at some distance beneath the surface, and have solidified much more slowly than volcanic rocks. As a result of this they have generally attained a much more coarsely crystalline granular st excepting along lines of contact. Plutonic rocks are often seen to rise through the strata and form low dome-shaped masses, known as laccoliths. Intrusive sheets which have found their way along the bedding planes of the stratified rocks may sometimes be mistaken for contemporaneous lava flows which were buried in the sediments when they were being formed. By a careful study of the contact phenomena the two cases can, however, usually be discriminated.

It is often found that both igneous and sedimentary rocks have been altered in such a way that new structures have been superinduced upon them, and new minerals have been developed within them. This process of alteration is known as metamorphism, and the rocks which have undergone it are known as metamorphic rocks. Two kinds of metamorphism have been recognized, namely, dynamic and contact. In the former the original constituents of the rock have suffered deformation, the grains in the sedimentary rocks and the crystals in the igneous rocks having been broken up into minute granules, some of which have been reconstructed into lenticular folia. In some cases a complete recrystallization of the mass has taken place. In dynamic metamorphism this change has been produced by the intense pressure to which these rocks have been subjected owing to the secular cooling of the earth's crust. The original bedding planes of the sedimentary rocks have in many cases been thrown into innumerable sharp folds, and secondary divisional planes, known as cleavage or foliation planes, have been developed in them.

In contact metamorphism the alteration in the rock has been produced by the intrusion of a mass of molten

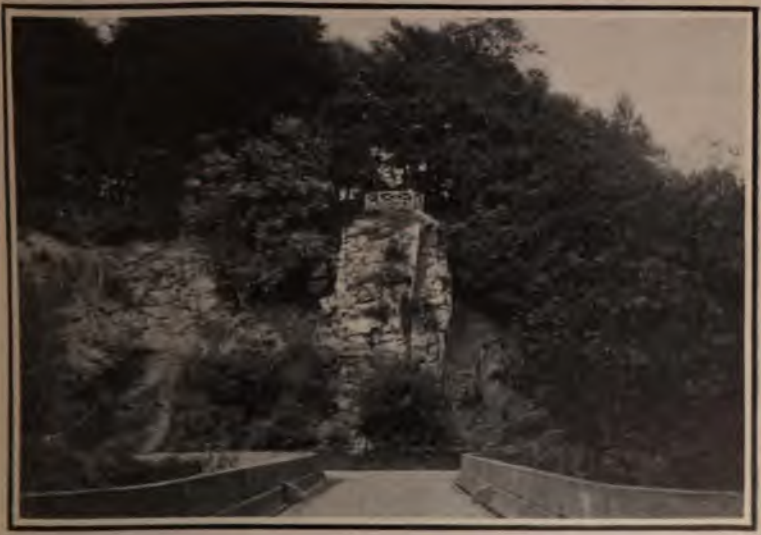


FIG. 1.—Dyke of Igneous Rock intruded into Sandstone,
Dalerne Bridge, Almondbank.

Photo. by the late MAGNUS JACKSON.

THE NEW YORK
PUBLIC LIBRARY

rock, which has baked and altered the rocks into which it has been intruded. A common result of such metamorphism is the development of new minerals in ordinary sedimentary strata near the line of contact. Under the microscope these embryo-crystals are often far more vague than when seen in the rock mass, and appear to shade imperceptibly into the amorphous, or granular, ground mass. Pyrites, mica, chiastolite, andalusite, and staurolite are some of the minerals which are usually developed by contact metamorphism. Signs of cleavage, or even a feeble foliated structure, are sometimes seen to accompany contact metamorphism, thus indicating that a certain amount of earth-pressure must have taken place. The Highlands of Scotland present a region in which all the phenomena connected with dynamic, and contact metamorphism may be studied in their most minute details.

The three principal methods used by geologists in determining the age of stratified rocks are known as the law of superposition, the law of contained fragments, and the law of organic remains. In an ordinary section of strata the newest rocks are at the top and the oldest at the bottom. But sometimes the rocks have been so folded and faulted that it is difficult to determine from apparent superposition alone which is the oldest and which the youngest bed. The second test for bedded rocks is that of included fragments, as a rock is necessarily newer than that of whose fragments it has been built up. The most unfailing test of the age of a rock is by the organic remains which it may contain. In the Grampians all trace of organic remains has apparently become entirely obliterated, so that this test is not available for the rocks that enter into their structure. They have also been so extremely faulted, folded, and in many cases inverted, that it becomes difficult to arrive at any conclusion regarding their order and relative age from the law of superposition alone. In a few instances the sedimentary rocks of the Grampians have been observed to contain fragments of an older set of rocks, and the relative ages of the two rocks have thus been determined. But the great mass of altered sediments of which the Highlands are composed points to one long period of continuous sedimentation, without any violent breaks or unconformities.

So absolute has been the destruction of all life by these deforming processes acting upon whole regions of fossil-bearing rocks, that not a vestige of the life they once contained has been left behind. Invariably the last traces of marine life to disappear are the burrows of the errant annelids; thus the weak things of the earth are made to confound the mighty, and while a great army may march across a desert with flying pennon and blare of trumpets, or whole nations disappear and leave not a vestige to mark their former existence, the track of a worm that crawled across the surface of the sea-shore millions of years ago may be sealed to all eternity upon the rocks. The same rule holds good in the processes of mountain building, so that when the rocks have lost nearly all traces of their original clastic structure, we can still detect, from the presence of these worm-tubes, evidence of their original birthplace beneath the bosom of the great deep.

In the cycle of its existence a rock may pass through all the different phases which have just been described. We have seen that under the influence of the weather, the rocks upon the surface of the earth gradually decompose and disintegrate, the loose material being carried onward into the sea by rills, brooks, and rivers. In the course of time a great thickness of sediments would be accumulated; and by the outpouring of igneous material, rocks that were once upon the surface would become buried deep in the interior of the earth, so as to come under the influence of its internal heat. Further, these rocks may then become involved in the complex processes of mountain building and be subjected to intense heat and pressure, so as to undergo quite a reconstruction of their original mineral constituents, when they pass into what we have described as metamorphic rocks. It ought to be borne in mind, that this change does not create new rocks, but only alters the old ones.

The crustal movements to which the metamorphism of rocks is due may also have raised them into great mountain masses above the sea. Immediately after their upheaval they again become the prey of the denuding agents, and the once deeply buried metamorphic rocks become exposed, only to pass once more through the great cycle of disintegration and change. In this way we see that the old rocks are being continually destroyed to provide material for the formation of new ones. The history of a rock has been classified into the following three stages: (1) the stage of its origin, which includes the period during which it was in an unaltered state; (2) the stage of its alteration; (3) the stage of its disintegration.

Over a century ago James Hutton published in

Edinburgh his *Theory of the Earth*, and in that great work he laid the foundation of physical and dynamical geology. Setting aside the wild dreaming speculations of the catastrophists, who sought to account for the geological phenomena exhibited in the crust of the earth by cataclysms, convulsions, inundations, and collisions with comets' tails, he insisted that in all our investigations into the past history of the earth "no powers are to be employed that are not natural to the globe, no actions to be admitted of except those of which we know the principle, and no extraordinary events to be alleged in order to explain a common appearance."

Hutton divided his original treatise into four parts. In the first two of these he discussed the origin of rocks, and following the principle laid down above he showed that the present rocks (with the exception of those which are not stratified) such as sandstones, clays, pebble deposits, and limestones, must have been accumulated on the bed of the ocean. Hutton further maintained that there must have been some powerful agency at work that converted the loose deposits into solid rock. To account for this he advanced the theory that at a certain depth the combined influence of subterranean heat and superincumbent pressure is sufficient to consolidate the loose material into coherent rock-masses, and even to convert them into a crystalline condition. From this it will be seen that Hutton had completely grasped the meaning of the great cycle of rock existence.

In the third part of his work he sought to show that the present existing land surfaces are to a large extent composed of rock-masses which have been accumulated

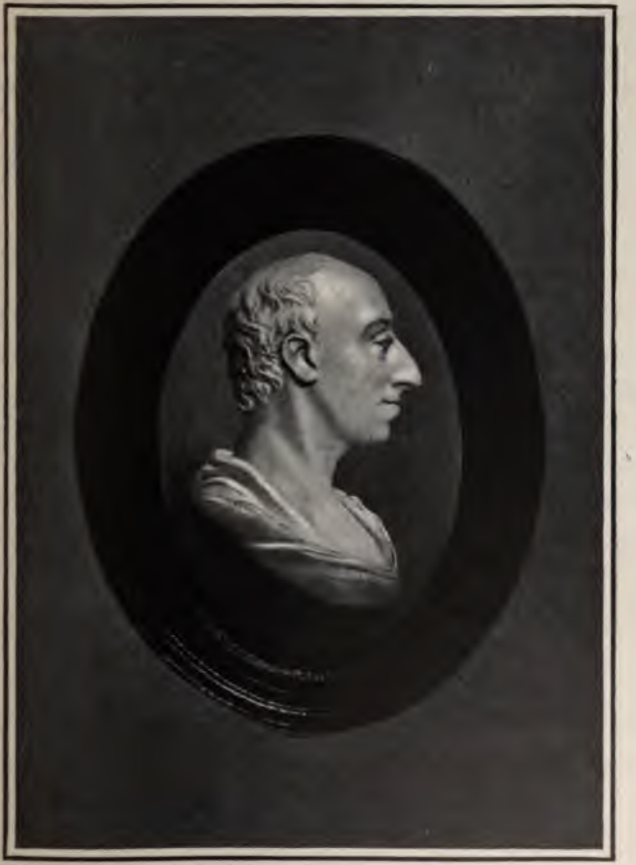


FIG. 2.—JAMES HUTTON.

(From a medallion in the Corporation Museum, Glasgow.)

in the bed of the ocean; these, he maintained, must originally have been laid down in an approximately horizontal position. They are now, however, found possessing all degrees of elevation, and in some cases they are seen to be vertical. He ascribed the present positions of the once horizontal rocks to the expansive force of heat which pushed the strata upwards and bent and tilted them during the process of upheaval.

In reasoning from the phenomena connected with the present visible evidence of the action of subterranean heat, Hutton showed how modern lavas might be compared with ancient igneous rocks and also in what manner they differ from them. He also pointed out how igneous rocks, where they came in contact with the surrounding strata, baked and indurated them.

Perhaps his most remarkable achievement in connection with the origin of igneous rocks was his determination of the nature of granite. In his first paper dealing with the theory of the earth, he came to the conclusion that granite had been "consolidated by heat and had at least in some parts been in the state of perfect fusion." Still, he had not been able to decide whether it was not rather a body transfused from the subterranean region, and made to break and invade the strata, in the manner of our whinstone and trap, and of porphyries into which the whinstone often graduates.

In his biographical account of Hutton, Playfair tells that, having chanced to mention the subject to the Duke of Atholl, Dr. Hutton and Mr. Clerk of Eldin were invited by his Grace to his hunting seat at Blair during the shooting season, "where," says Hutton, "I saw the most perfect evidence that the granite had been made to break the Alpine strata and invade the country in a fluid state."[1] "No less than six large veins of old granite in the course of a mile," says Playfair, "were seen traversing the black micaceous schistus." "This," his biographer says, "so filled Hutton with delight, that the guides who accompanied him were convinced that it must be nothing else than the discovery of a vein of silver or gold that could call forth such strong marks of joy and exultation."[2] This discovery enabled Hutton to arrive at the conclusion that granite, which had hitherto been regarded "as being the original or primitive part of the earth, is now found to be posterior to the Alpine schistus."[3]

After the time of Hutton, when Scottish geologists first began the investigation of the Highlands, it was supposed that the rocks of which they are formed had been laid down at the bottom of some primeval ocean, under conditions which could only have existed when as yet our globe was encased in a thermal ocean, and the crystalline character of the schists was accounted for by supposing that they had been precipitated in a liquid condition from that ocean. In like manner, the investigators of the tectonics of the Grampians had been led to propose special and often complex theories to account for the structures they had observed in them. But in both cases these positions have been abandoned, and the doctrine of uniformity has again gained a brilliant triumph. On the one hand, we find that the sediments out of which the great mountain masses of the Grampians have been built were deposited in exactly the same manner as the sand upon the sea-shore at the present day; and, on the other hand, the complex mountain structures which they exhibit have been developed according to those principles of mountain-building which have prevailed, so far as we know, throughout all geological time.

---

[1] *Trans. R.S. Edin.* vol. iii. p. 79.

[2] Playfair's *Works*, "Life of Hutton," vol. iv. p. 79.

[3] *Trans. R.S. Edin.* vol. iii. p. 81.

No geologist now doubts that these strata are altered sedimentary deposits—mud, silt, or sand—thrown down on the bottoms of ancient seas, and changed into a crystalline condition by heat and pressure generated in the contraction of the earth's crust. This great principle is essentially a fruit of Scottish geology. First taught by Hutton and Playfair, its best known and strongest evidence has ever been drawn from the rocks to which they appealed. To quote Playfair's own words upon the point: "How often," he says, "these vicissitudes of decay and renovation have been repeated, it is not for us to determine. They constitute a series of which we neither see the beginning nor the end, a circumstance that accords well with what is known concerning other parts of the economy of the world. The Author of nature has not given laws to the universe which, like the institutions of men, carry in themselves the elements of destruction. He has not permitted in His works any symptom of infancy or of old age, or any sign by which we may estimate either their future or their past duration. He may put an end, as He no doubt gave a beginning, to the present system, at some determinate period, but we may safely conclude that this great catastrophe will not be brought about by any of the laws now existing, and that it is not indicated by anything we perceive."[1] In the fourth part of his work Hutton directs attention to the former existence of continents and islands, from the disintegration of which the materials were derived that went to form the more recent land areas. He also discusses the former existence of plants and animals upon the earth, and shows that the faunas and floras at present living upon the globe must have sprung from these. The existence of these ancient faunas implies an abundant vegetation, and we have direct evidence of this in the coal and bituminous deposits of the Carboniferous and other formations.

From this Hutton proceeds to set forth, in passages that have become classic in geological science, the changes to which rocks are subjected when raised into the atmosphere. He describes the slow processes of sub-aerial denudation, both chemical and mechanical, and impresses upon his readers the vast periods of time that were necessary to complete any such cycle of destruction and reproduction. In proof of this he points out the comparative slowness with which changes take place upon the surface of the globe at the present time. Playfair says, when referring to this section of his work: "Here he finds without any exception that they are all going to decay; that from the shore of the sea to the top of the mountain, from the softest clay to the hardest quartz, all are wasting and undergoing a separation of their parts. The bodies thus resolved into their elements, whether chemical or mechanical, are carried down by the rivers to the sea, and are there deposited. Nothing is exempted

---

[1] Playfair's *Works*, "Illustrations of the Huttonian Theory," vol. i. p. 130.

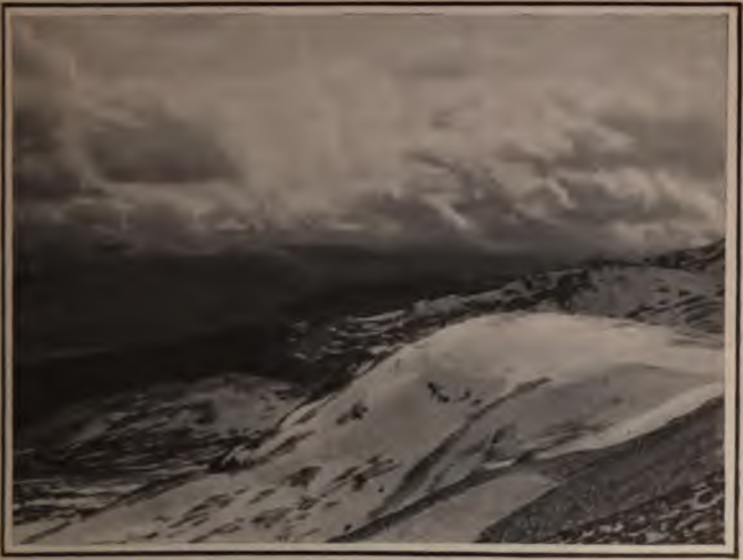


FIG. 3.—View from Ben Ghlas, looking to Killin, Glen Dochart, and Ben More.

Photo. by J. W. REOCH.

from this great law: among the highest mountains and the hardest rocks its effects are most clearly discerned; and it is on the objects which appear the most durable and fixed that the characters of revolution are most deeply imprinted."

Hutton, then, may be looked upon as the great founder of physical and dynamical geology. It was he who for the first time correlated the processes of denudation and deposition, showing how new continents have been formed by the destruction of still older ones, the material out of which the new land has been formed having arisen from the bed of the ocean and another land surface having taken the place of a still earlier one. In these apparently endless cycles of change he can find no vestige of a beginning—no prospect of an end: and though the physicist may be able to show that the earth exhibits within itself traces of a beginning and symptoms of an end, yet the forces that the geologist calls into play are so slow and gradual in their operation that he may safely assert with Hutton that no perceptible deviation has taken place in their mode of action since the deposition of the oldest rock systems.

We have often found ourselves overtaken on some lofty ridge of the Grampians by the rapid descent of night, and after a long day's work we have shouldered our bagful of specimens and begun the descent for home. Then, while the sunlight was fading in the west, peak after peak, in almost interminable succession, would be silhouetted against the sky, standing like Druids of old, indistinct in the twilight, with voices sad and prophetic. To the ordinary eye these vast mountain masses appear as the very type of all that is strong, and all that is enduring. They are, indeed, the everlasting hills, fit emblems of the fatal Being before whom man and his works are but the creatures of a day. Measured by the brief span of a human lifetime, they appear to be incapable of change. The outlines are the same familiar forms, known and loved since our earliest childhood, and our fathers have told us that to their eye there has been no perceptible change, while tradition connects events that have occurred ages ago with some particular crag or valley far up the mountain side, so that amid all that is evanescent we might well say with the Psalmist, "I will lift up mine eyes unto the hills from whence cometh mine aid."

But we must close this reverie for a moment, as we have reached a somewhat difficult position in the descent, where we must walk warily. It is, indeed, a wild and rugged place, and we have to clamber over huge rocks and boulders strewn in chaotic confusion over the mountain side, just as they were torn countless ages ago from the storm-splintered cliffs that tower above us.

The intense loneliness that exists here is indicated by the track of the fox through yonder snowdrift or by a ptarmigan's feather lying amongst the stones. The stars are now beginning to appear in the sky, the twilight being yet strong enough to exhibit the brown shoulders of distant hills, powdered with a thin layer of snow, and far away on the horizon, peak beyond peak glistening in its robes of pure white. Below lies the loch, reflecting from its calm surface every stone and tree, every tone and colour of the mountain above.

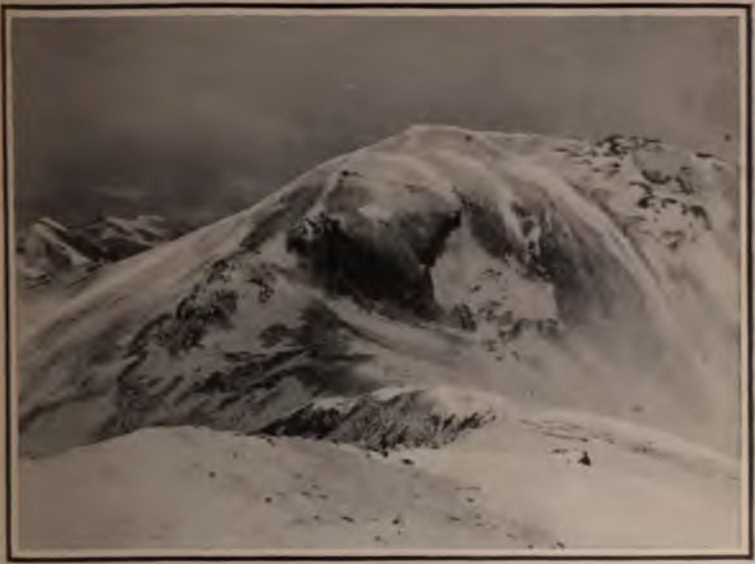


FIG. 4.—Ben Lawers, from the summit of Ben Ghlas.

Photo. by J. W. REOCH.

Reaching lower ground we again relapse into a spirit of reverie. The mountain glory has departed, and is followed by the equally awe-inspiring mountain gloom, as the darkness of a winter night slowly envelops the landscape. Then the still small voice insinuates the transientness of human life; we are only watchers from a ruined tower; it is not possible for us to reach any real height, because the scale shows no trace of a beginning, or of an end. Countless ages ago these great mountains came from the deep, under causes exactly the same as those operating around us at the present moment, and countless ages hence they will again return to their place of birth.

CHAPTER II

HISTORICAL INTRODUCTION

> Now who shall arbitrate?
> Ten men love what I hate,
> Shun what I follow, slight what I receive;
> Ten, who in ears and eyes
> Match me; we all surmise,
> They, this thing, and I that; whom shall my soul believe?
>
> ROBERT BROWNING.

THE remarkable confirmation which the famous researches of James Nicol on the structure of the north-west Highlands received at the hands of Professor Lapworth and the officers of the Geological Survey has now become a matter of history.

Nicol's paper was originally read on 5th December, 1860, and subsequently published in the *Quarterly Journal* of the Geological Society of London. The far-reaching conclusions which it involved were set aside by the great weight of such names as Murchison, Harkness, Ramsay, and Geikie, who opposed them in favour of a certain hypothetical succession; in this opposition Scottish geology received a blow from which it was destined not to recover for a space of nearly twenty years. Professor Lapworth reawakened an interest in the study of the Highland problem with the result we have just mentioned. This was followed by the detailed mapping of the north-west Highlands by the officers of the Geological Survey, the consequence of the whole being that a new impetus was given to the study of the Highland rocks, which has continued since that time. It must be confessed, however, that little advance has been made upon the general principles laid down by Nicol both for the north-west and southern Highlands, although the unravelling of the minute details of these regions has tended in a remarkable way to confirm the broader generalizations of that famous stratigrapher; and has brought us face to face once more with many interesting problems in the structure, succession, and metamorphism of those Highland rocks, which for so long a period had been entirely neglected.

In the first part of this chapter we propose to glance at those memoirs which were published by Murchison and Geikie, Harkness, Jameson and Nicol, on the geological structure of the Grampians about the years 1860-63; and we hope to be able to show that Nicol had already grasped the main features of the geological structure of that region, and that he maintained his views against the opposition of all the leading geologists of his time. We shall then proceed to a review of some of the more recent investigations into these rocks, which will bring us up to the present time and show us the remarkable confirmation which Nicol's work has received alike for the southern Highlands as for the north-west.

In their papers on the altered rocks of the Islan and north-west and central Highlands of Scotland, published in 1861, Murchison and Geikie[1] describe certain sections along the margin of the southern Grampians, with reference to the supposed succession of the rocks in the north-west. Briefly put, it was believed that the southern and central Highlands were overlaid by a great series of quartzites, limestones, and schists, the representatives of those found in the north-west of Sutherlandshire, and that they always occupied the same relative positions to one another—namely, the quartzites at the base, these followed by the limestones, and the whole overlaid by the schists. Let us now glance at the manner in which these authors read this supposed succession into the rocks of Highland Perthshire. In their description of the area between Tyndrum and the head of Loch Tay, Murchison and Geikie refer the higher reaches of Glen Dochart to the so-called upper schistose group, while the quartzose group is ushered in near the bottom of the Glen along with the limestones. A similar structure was supposed to exist in the case of Loch Tay and Ben Lawers, the limestone exposed along the base of the latter mountain and both sides of Loch Tay marking the division line between the upper schistose series and the lower quartzose group. From the following sentences we would infer that the authors did not look upon the Loch Earn and Loch Tay limestone as being upon the same horizon, and it also appears that they did not quite understand the relationship of the limestone band towards the south. "We are not aware," they say, "how far the limestones stretch towards the south-west. Those of Lochearnhead appear to belong to another arch. Towards the north-east of Loch Tay they are soon lost, but reappear in the valley of the Tummel at Pitlochry."

---

[1] Murchison and Geikie, "On the Altered Rocks of the Western Islands of Scotland and the North-Western and Central Highlands," *Quart. Journ. Geol. Soc.* vol. xvii. page 171. 1861.

In their description of a cross section from Loch Tay to Loch Rannoch, a succession similar to the foregoing was there supposed to be traceable, the schistose rock around Kenmore being referable to their upper group, while the quartzites of Schichallion were supposed to underlie these schists, and, with its limestones, to represent their lower group. Passing now to their next traverse, namely, that from Dalnacardoch to Blair Atholl, a great series of quartz rocks in an ascending order is described, terminating in the superposition of a very thick limestone series, two miles and a half from Blair. We quote the authors' own words in description of the Blair Atholl region: "In examining the south-western flanks of the Grampian chain near Blair Atholl it was indeed quite manifest, judging even from the flaggy and schistose characters of the rocks, that we were already among strata superior at all events to the lower quartz rock and limestones of the north-west Glossy Shillat, while micaceous schists, resting upon granular quartz rocks and limestones, and even alternating with them, presented to the eye a mineral development unknown in the lower members of the altered Silurian rocks of the north-west, and wholly unlike anything in the Cambrian rocks and fundamental gneiss of the outer Hebrides and the west coast of Sutherland."

In concluding our review of these authors' sections describing the relationship of the schists and quartzites of the southern Grampians, we would here notice their description of a traverse from the Spital of Glen Shee to Blairgowrie and from Blair Atholl to Dunkeld. In the former of these we pass across a complete series of the rocks forming the southern Grampians, and as Nicol subsequently described the same section, it will be of some value to compare Murchison and Geikie's work with that of Nicol. It is not very clear in Murchison and Geikie's paper what they consider to be the exact relationships of the black schists of the Spital of Glen Shee and the quartzites of Ben-y-Ghloe to the mica-schists, quartz-schists, clay-slates, and greywackes along the margin of the Grampians, as seen to the north of Blairgowrie. But it is likely that they looked upon the Ben-y-Ghloe quartzite as underlying these other rocks in a similar way to the quartzite of Schichallion and the region north of Blair Atholl.

The same remarks may be made regarding their description of the ground between Blair Atholl and Dunkeld. It is here again difficult to discover what Murchison and Geikie exactly refer to their lower quartzose group, and what to their upper schistose group. The rocks around Dunkeld, consisting principally of schists, grits, and clay-slates, are referred to their upper schistose series, and thus the whole problem of these marginal rocks seems to have been evaded.

It is unnecessary that we should enter into any further description of these sections, for what we have already given is sufficient to show that the main contention of these authors was that in the southern Grampians we have a great series of quartzites overlaid by limestones and schists. How thoroughly the true structure of the southern Grampians escaped their notice, and how much they were under the influence of this preconceived succession, will be better understood when we come to consider Nicol's paper, which was published shortly afterwards. Mention may here simply be made of the paper by Harkness on the structure of the Southern Highlands, as it follows much the same lines as that of Murchison and Geikie, adopting as he did their theory of succession. In all his sections, including those from Callander to Loch Earn, from Loch Earn to Loch Tay, from Loch Tay to Glen Lyon, and from Dunkeld to Blair Atholl and Ben-y-Ghloe, he recognizes the same succession of quartzites and limestones, overlaid by a great series of schists.

We now proceed to examine the famous paper of James Nicol,[1] published in 1863, on the Geological Structure of the Southern Grampians. Geikie, Murchison, and Harkness, as we have already seen, had published their papers, which were based on a hypothetical succession supposed to have been discovered in the north-west of Sutherlandshire. Nicol, however, was free and untrammelled by any such theory, if we except, perhaps, a tendency towards the Wernerian doctrine of the succession of the crystalline rocks. At the outset of his paper he states the object of it, which was to examine the relations to each other of each of the three great formations,—the clay-slate, the mica-slate, and the gneiss,—which, with some subordinate groups, such as quartz-rock and the chlorite series of Macculloch, had hitherto been regarded as composing the chief stratified masses in the Scottish

---

[1] "On the Geological Structure of the Southern Grampians," *Quart. Journ. Geol. Soc.* vol. xix. p. 180. 1863.

Highlands. Nicol's method was to begin at the south-west end of the Grampians, and, proceeding towards the north-east, he made a series of sections at different points across the Highlands, from the verge where they abut against the Old Red Sandstone, explaining their principal mineral and stratigraphical features, and comparing with one another the results arrived at in the various sections. He first of all notes the position of the clay-slates in the Island of Bute, showing that they dip towards the south-east at angles varying from 20 deg. to 60 deg., and appear to overlie the mica-schists of the interior. In his next section, that of Loch Long and the Gareloch, he notes a similar dip of the clay-slates towards the south-east at Rosneath at an angle of 40 deg., these in their turn conformably overlying the mica-schists and greywackes.

Passing now still further towards the east, the next locality which he describes is that from Ben Lomond to Balloch. In this section he again notes the occurrence of the clay-slates, greywackes, and mica-schists, the whole series being apparently conformable, and dipping at high angles towards the south-east. He makes the following remarks upon this group: "In this section, though the beds dip at much higher angles, the relation of the formations is still the same as on the Gareloch. The mica-slates dipping south are covered by an upper group of blue and green clay-slates and greywackes. The two formations also appear to be conformable, and the direction of the beds varies little from east and west by compass."

The next section is in Perthshire, namely at Callander and the Pass of Leny. Here, again, a similar series of rocks to that seen in the Ben Lomond section is described, but with this important difference, that they are now all seen to dip inwards upon the mountain chain. A detailed account is given in his paper, with exceedingly accurate measurements of the dip, of the beds of clay-slate, grits, greywackes, limestones, and mica-schists of Callander, the Pass of Leny, and Ben Ledi, and they are all shown to dip towards the north-west at greatly varying angles. With regard to this reversal of the dip he makes the following remarks: "The first general impression is that there is here a continuous series of beds dipping regularly to the north, the one below the other; in that case the greywackes to the south would be the lowest and oldest deposit, followed by clay-slate, and this by mica-slate, as the upper and newest formation. This is, of course, exactly the opposite order from that noted in the former sections, and cannot therefore be adopted without some consideration."

The next localities with which Nicol deals are those of Comrie, Strathearn, Loch Earn, Loch Tay, Dunkeld, and Blairgowrie. It is entirely unnecessary that we should here enter into a detailed account of his description of these sections. It will be sufficient for our purpose merely to indicate their larger features, and to show how these influenced his conclusion regarding the structure of the southern Grampians. At Comrie he notes the occurrence of greywackes and clay-slates exposed in the gorge of the Lednock, and gives their dip as averaging about 70 deg. north, 10 deg. west. He, however, afterwards refers these divisional planes to foliation, and not to planes of deposition. And he also believed that there was an unconformity between the clay-slates and mica-schists at this point. At Dunkeld and Blairgowrie he shows that the clay-slates and greywackes dip towards the north-west, and thus apparently under the main mass of the Grampians, which dip they retain onwards through the eastern Grampians to Stonehaven.

Passing now to a consideration of the general relationship of the clay-slates and mica-schists along the margin of the Highlands, as seen in the sections just described, he shows that in Bute and the Gareloch both the clay-slates and mica-schists dip to the south-east and are evidently perfectly conformable. At Loch Lomond he shows that both formations are nearly vertical, but have still a southerly dip. At Callander a reversal of the dip is noted, and now both formations dip to the north, which would make the mica-schists overlie the clay-slates. At Comrie he says they are unconformable, while at Dunkeld, Blairgowrie, and onwards towards the east, they are seen to dip inwards upon the mountain chain. Thus, in the eastern part of the mountain chain the clay-slates, grits, greywackes, and mica-slates seem all to dip towards the north, so that the mica-slates are upon the higher horizon, while at the western end of the chain all these rocks, which show every evidence of being physically the same series, dip outwards from the mountain chain and towards the south, the consequence being that the clay-slates must be looked upon as occupying the higher horizon. The following is, in his own words, the conclusion which he arrives at: "The analogy of other localities leads us to believe that the clay-slate is the higher and newer formation, and the lower inclination and more regular dip of the beds in Bute and on the

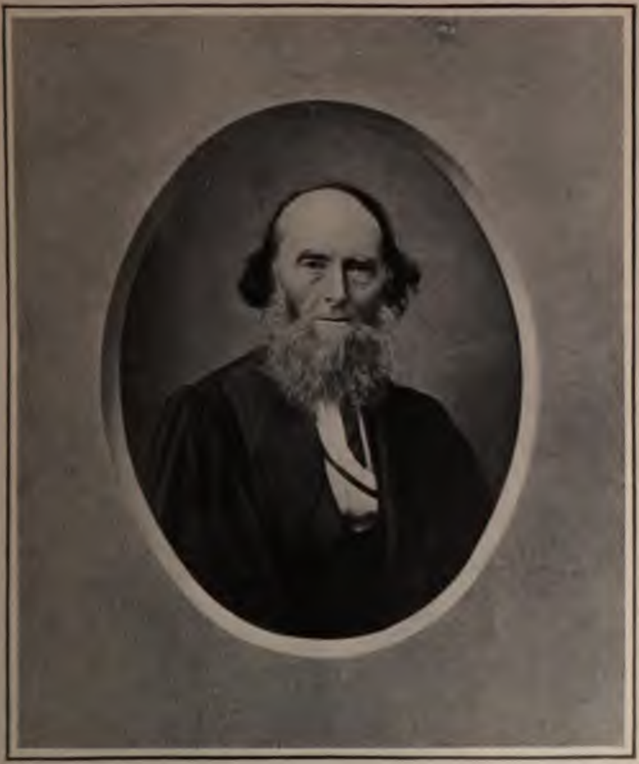


FIG. 5.—PROFESSOR JAMES NICOL.

(From a miniature in the possession of Professor James W. H. Trail, LL.D., F.R.S., Aberdeen.)

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS

Gareloch confirm the view that the strata are there in their normal positon. The reversed position, therefore, seen at Callander and other points to the north-east, must be abnormal." He then proceeds to show how this reversal of the beds has been accomplished, but this we shall pass over in the meantime.

We now come to a consideration of those sections which deal with the relationships of the central gneiss and quartzites to the mica-schists. Nicol mentions that as far back as the Leeds meeting of the British Association in 1858 he held that the great central formation of gneiss, quartzite, and limestone of the southern Grampians must overlie, and be younger than, the mica-schists. In a footnote he refers to the recently-published map of Murchison and Geikie, as showing that the gneiss, quartzites, and limestones of Glen Lyon, Blair Atholl, Schichallion, and Ben-y-Ghloe belong to a lower horizon.

The first section with which he deals is that of Tyndrum and the Black Mount, in which, tracing the schists from the head of Loch Tay to Crianlarich, he shows that they dip at low angles towards the north-west. After passing Crianlarich the dip is reversed, and he says that at this point there is probably a syncline. Proceeding further up the Glen towards Tyndrum, the mica-schists and limestone are seen to dip towards the south-east. From this point, along the road leading to Kingshouse and Glen Coe, the schists are seen to roll over and pass upwards into the quartzites and gneiss of the Black Mount. He further says: "This section left no doubt on my mind that the gneiss forming the great central region of the Black Mount overlies the mica-slate of Tyndrum and Loch Tay," and thus, as stated, is a newer formation. The next section in which he traces the relationship of the gneiss and quartzites to the mica-schist is that of Glen Shee and Braemar, also partly in Perthshire. We may here note, however, in passing, that he believed the same relationship to exist in the Valley of the Tay and its tributaries, though he had not been able to examine them for some time. The greater part of Glen Shee, he states, lies in the mica-slates, these beds showing a general inclination to the north. North of the Spital of Glen Shee he indicates a band of black carbonaceous shale dipping towards the north-west, and therefore conformable upon the mica-schists of the lower part of the valley, and compares it with the shales of Easdale and Oban. He also points to this bed as indicating the true position of these shales above the mica-schists. Proceeding up Glen Beg to the foot of the Cairnwell he indicates the existence of a bed of limestone still dipping to the north-west and overlaid by beds of gneiss and quartzite, and in his remarks upon this section says: "There is no doubt that the great formation of gneiss, limestone, and quartzite rests on the mica-slate of the southern Grampians, and is thus a newer formation. I have also no doubt that it is a continuous portion of the same great gneiss and quartzite formation which we have seen in the Breadalbane Highlands overlying the mica-slate of Loch Tay and Glen Dochart."

We need not follow the remaining part of this able paper, relating to the sections in the western Highlands. Enough has been given to enable us to perceive Nicol's general views upon the structure of the southern Grampians. *First*, that along the margin of the Grampians we have a series of grits, greywackes, and clay-slates lying in their normal position on the south-western part of the chain, but evidently being severally infraposed by faulting and a reversal of the beds along the north-eastern part of the chain; the clay-slates thus appearing to dip under the mica-schists as seen along the margin of the Perthshire Highlands. And *second*, that these mica-schists are overlaid by the quartzites, limestones, and gneisses of the central Highlands.

Let us now compare the conclusions arrived at by Murchison and Geikie with those of Nicol. As we have pointed out, the main contention of Murchison and Geikie was that the schistose rocks of the southern Grampians were always superposed upon the limestone, quartzite, and gneiss. We have shown that Nicol, in his paper, maintained that the quartzites of Ben-y-Ghloe, Glen Lyon, and Blair Atholl actually occupied a higher horizon than the mica-schists. We have already noted how thoroughly the structure of the marginal parts of the southern Grampians escaped the notice of Murchison and Geikie, and in the following part of this chapter we propose to show farther how the recent researches upon the structure and succession of the rocks of this region have tended to confirm the views of Nicol.

One is bound to admire the scientific skill displayed by Nicol in his attempt to solve the structure of the southern Grampians? First, in the method he adopted in choosing his sections; second, in the faithful descriptions which he gave of these sections; and lastly, in the masterly manner in which he compared them together and arrived at his conclusions as to their true structure.

We have dealt somewhat in detail with the contemporaneous work of Murchison, Geikie, and Nicol, and we have done so chiefly in order that justice may be done to the latter observer.

Undoubtedly Nicol's work in the Grampians was overshadowed by the magnificence of his discoveries in the north-west; but it would ill become us, even though now so late in the day, to allow it to be passed over in silence. None but those who have wandered amongst those lonely mountains, despairing of ever being able to wring from them the deeper secrets of their age and history, can realize the full depth and meaning of the words which Nicol used in reference to the opposition which his work received. In the preface to his *Geology and Scenery of the North of Scotland*,[1] for example, he says: "I would gladly have abstained introducing any controversial matter into these lectures, and been content with stating simply my own views, leaving time and the unchanging mountains to confirm or refute them." Again, when speaking of the supposed succession in the north-west, he says: "Again and again proofs of conformable upward succession have been adduced. Again, and yet again I have traversed these wild mountains, and one and all have vanished on closer inspection." We have often thought that there is a close parallel between Nicol's life-work and that of the old grammarian celebrated in Browning's immortal poem. With what peculiar fitness might such a funeral as was his, have been that of Nicol, and with what force of truth might these lines have been written for his epitaph:

---

[1] Nicol, *Geology and Scenery of the North of Scotland*, Edinburgh, 1866. See preface and p. 44. This almost forgotten little work is undoubtedly one of the classics of Scottish geological literature.

> "Here—here's his place, where meteors shoot, clouds form,
> Lightnings are loosened,
> Stars come and go! let joy break with the storm,
> Peace let the dew send!
> Lofty designs must close in like effects:
> Loftily lying,
> Leave him—still loftier than the world suspects,
> Living and dying."

We now proceed to a consideration of some of the more recent advances which have been made in the study of the structure and succession of the altered clastic rocks of the Highlands. In a summary of the "Rocks of Highland Perthshire,"[1] read by Mr. H. Coates and myself before the Perthshire Society of Natural Science in January, 1891, we gave an account of what we supposed to be the order and succession of these rocks as seen in Perthshire. In that paper we placed at the top the great arenaceous series of Schichallion, Blair Atholl, and Ben-y-Ghloe; then the mica-schists and quartz-schists of Ben Lawers and Loch Tay, with their limestones; and, below these, the arenaceous and argillaceous groups of the marginal Highlands. Subsequently, but in the same year (1891), in his Presidential Address to the Geological Society of London, Sir Archibald Geikie,[2] as the result of the work of the Geological Survey, arranged the altered rocks of Highland Perthshire in the following descending order:

---

[1] Coates and Macnair, "The Rocks of Highland Perthshire; their Origin, Plication, and Denudation," *Trans. Perth. Soc. Nat. Science*, vol. i. p. 221, 1891.

[2] Geikie, "Presidential Address to the Geological Society," *Quart. Journ. Geol. Soc.* vol. xlvii. p. 74, 1891.

17. Dark schist, calcareous schist, and limestone (Blair Atholl).
16. Quartzite (Ben-y-Ghloe, Schichallion).
15. Graphite schist.
14. Calcareous sericite schist.
13. Sericite schist with bands of quartzite (Canlochan, Glen Isla).
12. Garnetiferous mica-schist and schistose pebbly grits.
11. Limestone (Loch Tay).
10. Garnetiferous mica-schist and schistose grits.
9. Upper group of "green schists."
8. Garnetiferous mica-schists and schistose grits with pebbly bands.
7. Lower group of "green schists."
6. Thick group of massive grits, often abundantly pebbly, with partings of mica-schist phyllite. (Trossachs, Ben Ledi, Ben Vorlich, etc.)
5. Schists and shales, with occasional bands of pebbly grit (Loch Achray).
4. Band of conglomerate, with pebbles as large as a pigeon's egg (ridge between Lochs Achray and Ard).
3. Pale green, grey, and blue slates, with purple and red shales and bands of sandy flags (Aberfoyle).
2. Pebbly rusty-coloured greywacke and grit (Pass of Leny).
1. Black shales and flags, with lenticular bands of limestone, seen against the great fault at Callander.

The above is supposed to be a perfectly comformable series, the highest member, the dark calcareous schists of Blair Atholl, being placed at the top, while the black shales and limestones of Kilmahog, in the Pass of Leny, are placed at the exposed base of the whole series. With reference to the structure of the ground Sir A. Geikie remarks: "Over many square miles the angles of inclination are low and the successive bands may be traced from hill to hill, across strath and glen, forming escarpments along the slopes and outlines on the summits, precisely as gently undulating beds of sandstone and limestone may be seen to do in the dales of Yorkshire." In this address he proposes the term "Dalradian" for these rocks, to include the whole region lying to the south-east of the great glen, and the north of Ireland.

In his *Geological Map of Scotland*, published 1892, Sir A. Geikie[1] gives some of the results of the differentiation of these rocks by the officers of the Geological Survey, the principal additions in the map being the bands of graphite schist and sericite schist seen along the higher ridges of Loch Tay, and extending from Loch Fyne, in the west, into the eastern Highlands. The occurrence of two large faults is also marked; the one extending from Aberfoyle through Loch Lubnaig and Loch Tay and onwards through the higher reaches of Glen Tilt; the other running in a parallel direction from Luib, in the valley of Glen Dochart, through Glen Lochay, above the falls, and onwards into the eastern Highlands. This map serves to illustrate the succession given in the Presidential Address of 1891, the lower grits and greywackes being succeeded to the north by the mica-schists and limestones of Loch Tay, and these again in their turn being overlaid by the sericite and graphite schist bands of Tyndrum, Creag na Caillich, Ben Lawers, and Ben Vrackie, while the whole is overlaid by the quartzites and grits of Glen Lyon, Schichallion, Blair Atholl, etc.

---

[1] Geikie, *New Geological Map of Scotland*, 1892.

The next reference to these rocks which we have to note is that of Sir A. Geikie[1] in the third edition of his *Text Book of Geology*, published in 1893, where he says: "It is deserving of remark that the rocks along the southern margin of the Highlands are for the most part so little affected as closely to resemble portions of the unaltered Silurian series of the south of Scotland, and that they dip towards the mountains, becoming more foliated as they recede from the lowlands." He also here mentions the discovery by Mr. Peach of *radiolaria* in the cherts found associated with the graphite schist of the southern margin of the Highlands.

In a paper by myself,[2] published in the *Geological Magazine* for the year 1896, I have arranged the clastic rocks of the southern Grampians in the following zones, according to their predominant lithological characters. (See p. 41.)

It has been already pointed out, when dealing with Nicol's theory of the structure of the southern Grampians and the relationship of the clay-slates to the mica-schists, that he believed that along the margin of Highland Perthshire the clay-slates occupied an

---

[1] Geikie, *Text Book of Geology*, 3rd edition, 1893, p. 707.

[2] Macnair, "The altered Clastic Rocks of the Southern Highlands; their Structure and Succession," *Geological Magazine*, vol. iii. pp. 167 and 211, 1896.

TABLE OF THE ALTERED CLASTIC ROCKS OF THE SOUTHERN HIGHLANDS OF SCOTLAND.

ZONE.	ROCKS.	LOCALITIES.
Upper Arenaceous Zone.	Limestones. Quartzites.	Glen Tilt. Blair Athol. Glen Lyon, Schiehallion. Ben-y-Ghloe.
Upper Argillaceous Zone.	Graphite Schist. Sericite Schist. Quartzites and Greywackes, with Annelid Tubes.	Ben Lawers. Glen Shee. Loch Fyne. Ridge north of Loch Tay. Creag-na-Caillich, Ben Lawers, Killin.
Middle Arenaceous Zone.	Garnetiferous Quartz-schists and Mica-schists, with bands of Grit and Conglomerate.	Loch Tay. Loch Earn, Glen Dochart, Balquhidder.
Loch Tay Limestone Zone.	Pure Limestone and Micaceous Limestone.	Loch Tay, Loch Earn, Glen Dochart, Ashintully.
Middle Arenaceous Zone.	Garnetiferous Quartz-schists and Mica-schists, with bands of Grit and Conglomerate.	Loch Tay, Loch Earn, Glen Dochart, Balquhidder.
Lower Arenaceous Zone.	Massive Grits and Conglomerates. Grits, Greywackes, and Quartzites.	Ben Ledi, Ben Vorlich. Pass of Leny, Glen Lednock, Forneth.
Lower Argillaceous Zone.	Clay-slates and Phyllites. Limestone. Graphite Shale, Red and Purple Shale.	Aberfoyle, Loch Lubnaig, Pass of Leny. Kilmahog, Pass of Leny. Kilmahog, Pass of Leny.

abnormal position. His theory was that they did not really underlie the mica-schists, but that the latter are the older rocks, which have been pushed and faulted over the clay-slates. Now we find Sir A. Geikie, in his later Government Reports,[1] reverting, to a certain extent, to this old theory of

---

[1] Geikie, *Annual Reports of the Geological Survey of the U* *Kingdom for the Years* 1893, 1895, 1896, 1897.

Nicol's, and receding in part from the position taken up in his Presidential Address of 1891, and the succession there published. We quote from his Report for the year 1896: "In my Report for 1893 reference was made to a belt of rock, not improbably of Lower Silurian age, interposed along the Highland border between the schists on the one hand and the fault that brings down the Old Red Sandstone on the other. Mr. Clough was instructed to resume the examination of this belt between Aberfoyle and Loch Lomond. Notwithstanding his detailed mapping, to which reference has already been made, we are still unable to form a definite conclusion as to the structure of this difficult piece of ground. Mr. Clough is on the whole inclined to believe that between the black shales and cherts, which may be Lower Silurian, and the Aberfoyle grits which lie immediately to the north of them, and form apparently a continuous portion of the Highland rocks, there are indications of a discordance or stratigraphical break."

It is, however, admitted in this Report that a great difficulty arises in the attempt to fix any line of demarcation between these supposed younger rocks and the grits and phyllites presumably belonging to the Highland rocks. It is also admitted that these grits are no more altered than the shales and cherts of the supposed younger rocks, while, further, it is often observed that the shales, phyllites, cherts, and grits are so much interbedded as to point to the conclusion that they form one stratigraphical group. Again, to quote from the Report: "The obscurity of this boundary line has suggested the inquiry whether the Aberfoyle grits should not be grouped with the black shales and cherts as probably also of Lower Silurian age. But this explanation would only shift the difficulty farther north, for we would still have to find somewhere a southern line of demarcation for the schistose rocks of the Highlands. Certainly, so far as detailed investigation has yet gone, no such line is to be found between the Trossachs and Aberfoyle." It seems to us that these views are nothing more than a resuscitation of the old theory advanced by Nicol many years ago to account for the position of these less altered rocks along the margin of the Grampians.

In the Government Report for 1897 Sir A. Geikie states that Mr. Barrow has been enabled to distinguish a series of unaltered rocks along the marginal Highlands of Kincardineshire by a microscopic examination of their micas. In the slates and phyllites belonging to the crystalline rocks of the Highlands the micas show evidence of re-crystallization, while in the unaltered band of supposed Silurian age they still retain their original clastic appearance. Referring in the same Report to the work of Mr. Clough at Callander, Sir A. Geikie says they are still unable to come to any conclusion which will enable them to separate out the presumably Lower Silurian rocks from the phyllites and grits of the marginal Highlands, for similar reasons to those which we have already cited in our extracts from the Report for 1896.

Recently we had an opportunity of re-examining these rocks at Callander and Aberfoyle, for the purpose of seeing how far these views of the Survey could be maintained. We think that there can be no doubt that the whole of this marginal belt of grits, greywackes, and slates, extending from Stonehaven on the north-east to the Firth of Clyde on the south-west, belongs to the same group of rocks. The dominant north-east and south-west strike of the rocks forming the southern Grampians is one of their most characteristic features. Local variations in the strike undoubtedly occur, but, when we consider the extreme plication and twisting to which these rocks have been subjected, this is not to be wondered at.

A comparison of the lithological characters of the rocks at different localities along the margin of the Highlands also points to their all belonging to the same group or horizon, though at some points they show evidence of more extreme metamorphism than at others. Thus at Bridge of Cally, Dunkeld, and Callander they appear to be less altered than at Dunoon and elsewhere on the Firth of Clyde, where the slates pass into true phyllites and the grits become more mineralized. We also think there can be no doubt, from what we have seen, that the grits, slates, and phyllites are conformably interstratified with each other, and belong to one stratigraphical group. At Dunkeld and Birnam, in the quarries, this interbedding of the arenaceous and argillaceous types is well seen. To the north they pass upwards into the arenaceous group, as seen to the north of the Loch of the Lows, while to the south, as at Forneth, this areno-argillaceous zone passes downwards into beds of pure grit. Again, at Callander and Aberfoyle a similar lithological succession may be seen, namely, shales with bands of grit passing both upwards and downwards into pure grits.

We now pass on to consider briefly the structure

of this marginal belt of grits, greywackes, and phyllites, and the problem of their relationship to the more crystalline rocks. In Perthshire and the north-eastern Grampians, as was long ago pointed out by Nicol, these rocks have a dominant north-west dip, and seem to pass under the mica-schists, quartz-schists, and limestones of Loch Tay, which again pass upwards into the quartzites of Schichallion and Glen Lyon. Sir A. Geikie, in his Presidential Address to the Geological Society for 1891, already cited, notes the remarkable lowness of the dips in this region, and adopts the view that these slates, phyllites, and grits pass under and are older than the more crystalline rocks lying farther to the north. So far as we have been enabled to observe, there is no evidence of any stratigraphical break or overthrust between the quartz-schists and mica-schists of Loch Tay on the one hand, and the grits, shales, and phyllites of Callander, the Pass of Leny, Crieff, Comrie, and Dunkeld on the other. On tracing these rocks, however, towards the south-west, as was also shown by Nicol, the dips become gradually higher and higher towards the extreme south-western boundary of Perthshire, as at Aberfoyle. They have still, however, a north-westerly dip at this point, evidently passing under the limestones and schists of Glen Dochart, and thus bearing the same relationship to these schists as was seen to hold good in the last locality. On reaching Loch Lomond they become vertical, and from this point, along the shores of the Firth of Clyde, the dip is reversed, it now being towards the south-east, as at Dunoon and along the shores of Cowal,
thus they now, apparently, overlie the rocks fo

the interior of the Highlands. The relationship of this marginal belt of grits, greywackes, and phyllites to the main mass of the Grampians, and its structure, may be seen in the section from Kirn to the head of Loch Eck. Along the shores of Cowal these rocks are seen to dip, at angles varying from 40 to 70 degrees, to the south-east. Near Kirn pier, a series of beds of phyllites, greywackes, and black slates are seen interbedded with bands of limestone. Continuing the section up the Holy Loch, a great series of beds of lustrous phyllites, still dipping towards the south-east, may be observed. Near the head of the Holy Loch, they pass upwards into a more arenaceous group of grits and greywackes, having at this point a dip of 55 deg. to the south-east. Proceeding up Loch Eck some fine sections of these arenaceous rocks may be seen, evidently greatly disturbed, but still dipping towards the south-east.

We have already shown how Nicol was confronted with the problem of the relationships of these rocks, and how he decided in favour of the slates and phyllites being the younger rocks. He also believed that they were in their normal position, relative to the mica-schists of the interior, along the Firth of Clyde, while in the north-east, as in Perthshire, they had been faulted against these schists and were there made to appear as if they were older than the schists of the interior. Taking this marginal group of arenaceous and argillaceous rocks as a whole, we are inclined to think that in Perthshire we find these rocks in their normal position, and that there is there a perfectly conformable upward succession as shown in the tables already referred to, prepared by Sir A. Geikie, and by the author. Towards the north-east of the mountain chain, as in Perthshire, the north-west dip of the beds of phyllites, slates, grits, and greywackes indicates that these rocks form the southern limb of what appears to be a deep synclinal trough. Traced inwards towards the north-west, they are seen to pass upwards into the quartz- and mica-schists and limestones of Loch Tay and Ben Lawers, which rise to form the northern limb of an apparent syncline. From a comparison of the dips it seems that the southern limb of the syncline formed by the phyllites and grits abutting against the great fault is much steeper than the northern limb, and, so far as we can see at present, it seems to us that in tracing this southern limb from north-east to south-west across the mountain chain it gradually becomes steeper and steeper till it folds over and eventually, in the Firth of Clyde and Cowal district, is made to appear as if it overlay the higher group of quartz-schists and limestones, which it really underlies, as seen in Perthshire.

To the south of this zone of phyllites and grits, whose relationships we have just been discussing, occur certain beds showing a much less altered appearance than others. As we have already seen, Sir A. Geikie, in his Government Reports, mentions their occurrence at Aberfoyle, Callander, and in the river Esk, Kincardineshire. The beds in the latter locality containing *radiolaria* have a general appearance which seems to link them with the Arenig rocks of the Southern Uplands. From this he concludes that amongst this belt of grits and phyllites, which evidently belong to the crystalline rocks of the Highlands, there has been interposed a group of younger rocks, probably of Lower Silurian age, the most continuous section of these younger rocks being that seen in the Kelty Water, west of Aberfoyle. We have long been acquainted with this section, but can see no reason for separating these rocks out from amongst the grits and phyllites with which they are evidently interbedded.

The following may be taken as the general structure, succession, and lithological characters of the rocks seen at Callander, the Pass of Leny, and the Kelty Water. Immediately to the north of the line of fault, and exposed in Kilmahog quarry and the bed of the Kelty, lies a series of beds of graphitic shale, with lenticular bands of limestone, for which the quarry was originally worked, and which are seen to dip at angles of 50 degrees to the north-west. To the north of these less altered beds a series of purple shales with phyllites and beds of grit and greywacke occurs, dipping again at angles of from 50 to 60 degrees to the north-west, and evidently conformably succeeding the underlying and less altered beds. These again are succeeded by massive beds of grit and conglomerate, with zones of phyllites, as seen on the shores of Loch Lubnaig, passing eventually upwards into the mica-schists, quartz-schists, and limestones of Balquhidder and Glen Dochart, and showing, so far as we have been able to observe, no evidence of any stratigraphical break.

In conclusion, the structure, age, and relationships of this marginal belt of rocks seen in Highland Perthshire must still remain an open question. For the reasons we have already discussed we are still unable to accept Nicol's theory that the true position of this belt of arenaceous and argillaceous rocks is that seen in the south-western part of the mountain chain, while that shown in Perthshire is owing to faulting and overthrust.

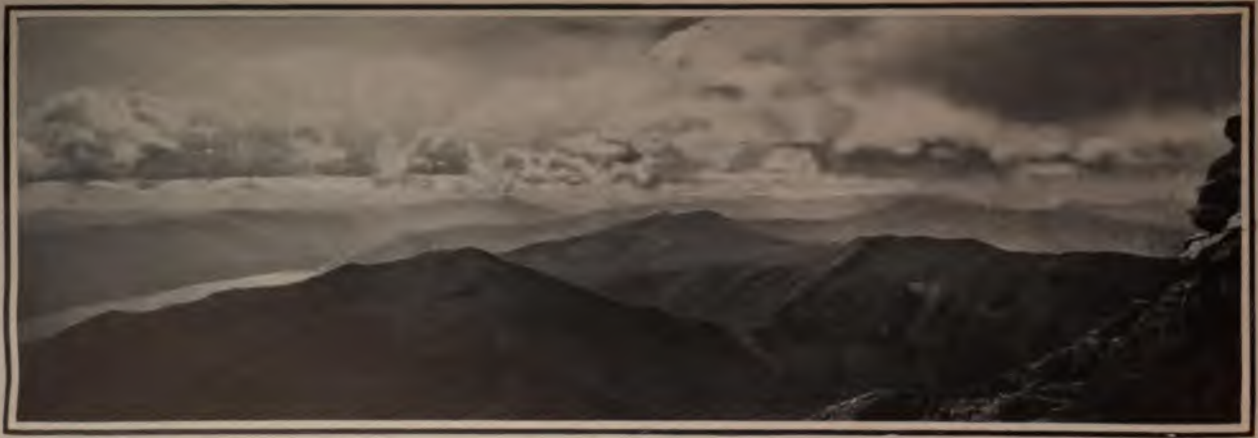


FIG. 6.—View from the summit of Ben Lawers along the Great Axial Line of Folding.

Photo. by W. LAMOND HOWIE, F.C.S.

Could this be definitely shown to be the case, then we could understand the position of these unaltered beds in this marginal belt. On the other hand, it would seem from the Government Reports that Sir A. Geikie would prefer to separate out these less altered beds from the main mass of the grits and phyllites, relegating the latter to the crystalline rocks of the Highlands. But he is unable to find any line of demarcation between the two. In the meantime, until further evidence is forthcoming, we are inclined to look upon this marginal belt of grits and phyllites, with the less altered beds of shale and limestone, as forming one stratigraphical group, conformably underlying, and older than, the schists and limestones of the interior. Nor do we think that the less altered appearance of certain of the beds militates against this view, as the amount of metamorphism varies exceedingly along the line of strike.

In a series of papers published within the last ten years the author[1] has gradually arrived at the conclusion that down the centre of the Highlands there passes a great axial line of folding, having a fan-shaped structure, from which the rocks have been thrown off towards the north-west and south-east in a series of isoclinal folds. Near the apex of the fan the isoclines are vertical, and on each side the axes of the folds dip inwards towards the north-west and south-east respectively. Traced towards the south-east the axes of the folds become flatter and flatter till they are almost horizontal. On approaching the Highland frontier the axes of the folds again begin to rise till they dip towards the north-west at a higher angle. In following certain lines of section from the apex of the fan towards the south-east, lower and still lower beds rise to the surface. On the apex of the fan we have the Upper Argillaceous Zone, further south the Garnetiferous Schist Zone, then the Loch Tay Limestone Zone, followed by the Lower Arenaceous Zone and the Lower Argillaceous Zone, seen along the Highland frontier. On the north-west side of this great axial line the arrangement of the schist zones is somewhat different, as the members of the Lower Arenaceous and Lower Argillaceous Zones, seen along the Highland frontier, do not appear to come to the surface, being everywhere covered by members of the series lying above the Loch Tay Limestone. To the south-east and north-west of this great axial line of folding there would be corresponding troughs, in which the isoclines would be arranged in a syncline or trough. In the centre of the trough the axes of the isoclines would be vertical, and on each side they would dip away in opposite directions, the troughs being bounded by fan-shaped structures, and the fan-shaped structures by troughs. In the eastern part of the Southern Grampians, and to the south-east of the great central *Fächer*, or fan structure, the schists are seen to be arranged in such a trough. Traced by Loch Lomond, and towards the Firth of Clyde, the axes of the isoclines, forming the most southerly portion of the trough, become gradually reversed, and are seen to dip towards the south-east. They probably form part of the northern limb of a fan, now cut off by the great boundary fault, and covered by younger Palaeozoic rocks, so that in the region between the Firth of Clyde and Loch Fyne the schists are arranged in an apparently anticlinal form, being in reality a trough. This structure deceived the earlier observers, and led them to believe that there was here a true anticline in the bedding; and latterly the officers of the Geological Survey formed the opinion that there was here a great anticline of foliation.

---

[1] Macnair, "The Geology of Creag-na-Caillich and the District round Killin," *Trans. Perthshire Society of Natural Science*, vol. iii. part iv. page 155, 1902.

Macnair, "The Crystalline Schists of the Highlands," *British Association for the Advancement of Science*, page 414, 1901.

Macnair, "Report of Glasgow Meeting, 1901," *British Association for the Advancement of Science.*

Macnair, "The Building of the Grampians," *Trans. Royal Philosophical Society of Glasgow*, vol. xxxiv. page 147.

We now proceed to a consideration of some of the more recent advances which have been made in the study of those altered basic rocks known as epidiorites and hornblende-schists. It is not necessary that we should here enter into any of the earlier opinions held concerning these rocks. Of all the schists found in the Highlands, these hornblende-schists seemed to lend the most support to the old view that they had been precipitated from the thermal waters of some primeval ocean, the presence of hornblende, garnet, and other minerals in a highly crystalline condition, seeming to support this view of the origin of these rocks. But from the advance of our knowledge concerning the changes which have been produced upon both igneous and aqueous rocks by dynamic metamorphism, it is now well known that most of these schists were originally ordinary sediments, and even igneous rocks, upon which a foliated or schistose structure has subsequently been superinduced by the straining and shearing of the rocks.

It was in the district of the Lizard, in Cornwall, that these hornblende-schists were first studied in detail by Professor Bonney. In his earlier papers on that district, Professor Bonney expressed the belief that these rocks were of aqueo-volcanic origin, and that the planes of foliation corresponded to the original planes of sedimentation. He even thought that he could detect in them lines of current-bedding. In a paper giving the results of a re-examination of these rocks by Professor Bonney and Major-General C. G. M'Mahon, and published in the *Quarterly Journal of the Geological Society* for 1891,[1] the authors admit that the hornblende-schists are, in part at least, of igneous origin, and explain their banded structure by movements in the mass previous to consolidation, these views being more fully developed in subsequent papers.

Perhaps the most important of all the later contributions made towards the study of these rocks, and one from which we may date the beginning of the more recent researches into their structure and origin, is a valuable paper by Mr. J. J. H. Teall, contributed to the Geological Society of London in the year 1885.[2] In this paper he shows that two more or less parallel dykes intruded into the archaean gneiss of Western Sutherlandshire have been altered from their original structure as an intrusive dolerite into a hornblende-schist, and that this alteration has taken place after the dolerite had become consolidated, the change having been brought about by dynamo-metamorphism. He shows that even in hand specimens taken from this dyke a distinct passage can be traced from the dolerite into the hornblende-schist. The following may be taken as a summary of the results arrived at in the paper: (1) That the hornblende-schist has been developed from a dolerite by causes operating after the consolidation of the dolerite, and that the metamorphism has been accompanied by a molecular re-arrangement of the augite and felspar; (2) that the molecular re-arrangement has in certain cases taken place without the development of foliation; and (3) that the plasticity which has led to the development of foliation is that due to high pressure at ordinary temperature.

---

[1] Bonney and M'Mahon, "Results of an Examination of the Crystalline Rocks of the Lizard District," *Quart. Journ. Geol. Soc.* vol. xlvii. p. 464.

[2] Teall, "The Metamorphosis of Dolerite into Hornblende Schist," *Quart. Journ. Geol. Soc.* vol. xli. p. 133, 1885.

In the year 1887 another important contribution towards the study of these rocks was published in the *Geological Magazine*[1] by Mr. J. J. H. Teall, in which he proposed to account for the banded structure seen in certain gneisses of the Lizard, on the hypothesis that they had been originally igneous rocks associated together as a plutonic complex.

In a paper contributed to the Geological Society of Glasgow in the year 1896,[2] the author gave an account of that extensive sill of basic igneous rock which underlies the Loch Tay limestone, and is generally seen to outcrop along with the limestone. It may be studied near the village of Killin, at the south-west end of Loch Tay, where it is exposed in several fine sections. Along the road which leads to the steamer pier, and in the woods of Finlarig, the hornblende-schist may be seen in contact with the limestone. At this point the limestone dips towards the north-west at an angle of 45 degrees, and is underlaid by this sill of basic rock. The relationship of the basic rock to the limestone may also be well seen in the southern front of Sron Clachan, from which point it may be traced to the south side of Glen Dochart near the head of Glen Ogle. Down Glen Ogle various exposures of the basic rock in contact with the limestone may be observed. Traced round to Glen Beich, a fine section of the hornblende-schist is exposed at the foot of that glen. The limestone and hornblende-schist may then be traced at various points to the head of Glen Beich, where some fine sections are exposed, showing the hornblende-schist and limestone traversed by numerous veins of pink quartz-felsite. An interesting outlier of limestone with the accompanying sill of basic rock may be seen at the summit of Meall na Creige, a mountain situated to the south-east of Ardeonaig. This mountain is also traversed by a series of mineral veins which were at one time mined for galena. We think there can be no doubt that this mass of basic rock must originally have been intruded amongst the clastic rocks in the form of a sill. At certain points, as in Finlarig Wood, Killin, the mica-schist shows evidence of a more extreme metamorphism along the line of contact with the hornblende-schist, which at various points shows evidence of breaking across from one horizon to another. Again, smaller sills, or apophyses, evidently connected with the main mass, may be seen at various points along the line of outcrop.

---

[1] Teall, "On the Origin of Certain Banded Gneisses," *Geol. Mag.* vol. iv. p. 484, 1887.

[2] Macnair, "On the Altered Basic Rocks of the Highlands, as Exemplified by the Sill of Hornblende Schist underlying the Loch Tay Limestone," *Trans. Geol. Soc. of Glasgow*, vol. x. p. 302, 1896.

Macroscopically, a specimen of the typical hornblende-schist is seen to be made up of alternating folia of light and dark coloured minerals, which under the microscope are seen to be felspar and hornblende. When the rock is highly foliated and shows a marked schistose structure, indicating that it has undergone a more or less intense metamorphism, the felspars generally exhibit a granular appearance, as if they were of clastic origin. This structure is now well known to be the result of the shearing of the rocks by earth creeps, which have crushed and broken the felspars into this granular form. In the more schistose types of these altered basic rocks the hornblende generally presents the characteristic long needle-like forms, or occurs as grains or irregular masses in the hornblende-schist. The amount of metamorphism which the sill has undergone seems to vary considerably at different points. Thus at Killin it has passed into a typical hornblende-schist, having at this point evidently undergone the maximum of change. On Meall na Creige and in Glen Quaich the structural change has not been so great, as at these points it does not exhibit the schistose structure, though the original component minerals of the basic rock show evidence of having undergone the usual changes consequent upon being subjected to the action of dynamo-metamorphism.

Many obscure and difficult problems still await solution in connection with these altered basic rocks. It is probable that when they have been subjected to a detailed examination they will be found to consist of different types of basic lava. Again, the conditions under which they were erupted is still a matter surrounded by much mystery; for while they generally show evidence of having been intruded as sills amongst the clastic rocks, as in the case of the mass underlying the Loch Tay Limestone, it is probable, on the other hand, that some of them may have been erupted at the surface as lava flows. This view is borne out by the presence of green chlorite-schists, which have evidently originally been volcanic ashbeds. It is often, however, very difficult to determine correctly what the original relationship of many of these masses of basic rock may have been. So completely have they been rolled out between the shearing planes of the mica-schists that their original lines of contact with the clastic schists have become more or less obliterated.

Turning now our attention to the Old Red Sandstone of Scotland, the physical conditions under which this was formed is a subject that has long occupied the attention of many of our leading geologists, from the time of Hugh Miller and Sir Roderick Murchison down to those of the present day. It has been variously regarded as of fresh-water, and as of marine origin ; as having been thrown down in lakes, in the open sea, or in inlets of the latter. But as yet the whole matter seems to remain an open question, which the unique physical and palaeontological elements of the formation make difficult of solution.

For a long time it has impressed the writer that much of the evidence freely assumed to be in favour of a fresh-water and lake origin for these deposits may, or may not, admit of proof; while, on the other hand, the evidence which is in favour of their entire extension over Scotland, and of their marine origin, has either been entirely overlooked or so minimized as not to be taken at its real value.

The first discoverers and workers amongst [illegible] rocks, Hugh Miller and Sir Roderick Mu[illegible] firmly believed in their marine origin ;

Hugh Miller was not so much a stratigrapher as a palaeontologist, yet he clearly realized the fact that the Old Red Sandstone must at one time have covered the whole of the Scottish Highlands, as in his *Old Red Sandstone*[1] he speaks of a sea that extended from Ben Lomond to the Maiden Paps of Caithness. Sir Roderick Murchison, on the other hand, entered into a detailed study of its stratigraphical and physical structure and relationship, and it is mainly to his views, we are persuaded, that the student of the Old Red Sandstone rocks of Scotland must finally return.

Stratigraphically, Murchison divided the Old Red Sandstone rocks of Scotland into three members—the upper, the middle, and the lower—each characterised by a distinctive fauna: the lower group, as seen in Scotland, being principally developed in Forfarshire and Perthshire, and characterised by *Cephalaspis* and *Pterygotus*; the middle group, seen in Caithness, and containing *Dipterus*, *Osteolepis*, etc.; while the third, or upper group, well developed in Dura Den, and containing *Holoptychius* and other characteristic forms, passes up conformably into the basement beds of the Carboniferous formation, there being always a decided break between the upper member and all the older rocks. He also correlated the Scottish Old Red Sandstone, with its deep-water equivalent—the Devonian of England and Russia—pointing out that in the latter country the Devonian rocks containing marine shells were also interstratified with red sandstones in which no shells were found, but which were replete with the piscine fauna common to the Scottish rocks.

Latterly, however, principally through the work of

---

[1] *Old Red Sandstone*, 7th edition, p. 53.

Goodwin Austen, Ramsay, and, more particularly, Sir A. Geikie,[1] the Old Red Sandstone of Scotland came to be looked upon as a fresh-water deposit accumulated in isolated basins. The researches of the two first writers were principally directed to the petrological characters of the rocks. The last writer was the first to isolate the Scottish areas of Old Red Sandstone into separate basins of deposit, with the distinctive names Lake Orcadie, Lake Caledonia, Lake Lorne, and Lake Cheviot, the Old Red Sandstone of Strathmore belonging wholly to the second of these lake areas. Sir Archibald Geikie believes that they were all contemporaneous, doing away with the existence of the Caithness rocks as a middle group, and explaining the discrepancies of their fossil contents on the ground that they are no greater than those of contiguous fresh-water basins at the present day. In his *Scenery of Scotland* he also presents some of the physical problems connected with the Old Red Sandstone and its formation. Sir Archibald Geikie and his brother, Professor James Geikie, may be looked upon as being the principal authorities for the isolated lake, and fresh-water, origin of these deposits. We believe, however, that when the general facies of the Orcadian fauna and flora is compared with that of the Caledonian, and their respective petrological and stratigraphical characteristics taken into account, the geologist will be driven by the overwhelming evidence to the conclusion that they represent two distinct periods in time, of which the Orcadian is the younger and the Caledonian the older.

---

[1] See "The Old Red Sandstone of Western Europe," *Trans. Royal Society of Edinburgh*, vol. xxviii, and *Text-Book of Geology*.

Every year sees the literature bearing upon the geology of the Grampians grow larger and larger, and now that the Geological Survey has completed the mapping of the ground, it is to be hoped that detailed memoirs describing each sheet will be issued. As a matter of fact, the memoir for sheet 55, which includes the Blair Atholl, Pitlochry, and Aberfeldy district, has appeared, and we hope that it will soon be followed by the others. We have made no reference to the work that has been done among the glacial and post-glacial deposits of the area under review, but what we have to say upon this subject will be treated under the chapters dealing with the superficial deposits. It is hoped that the historical method of approaching the study of the geology of the district will be of value to the student who is breaking ground upon it for the first time. For ourselves, nothing could possibly be more fascinating than the study of the gradual passage through the alembic of the human mind of such great problems as are presented by the rocks of central Scotland.

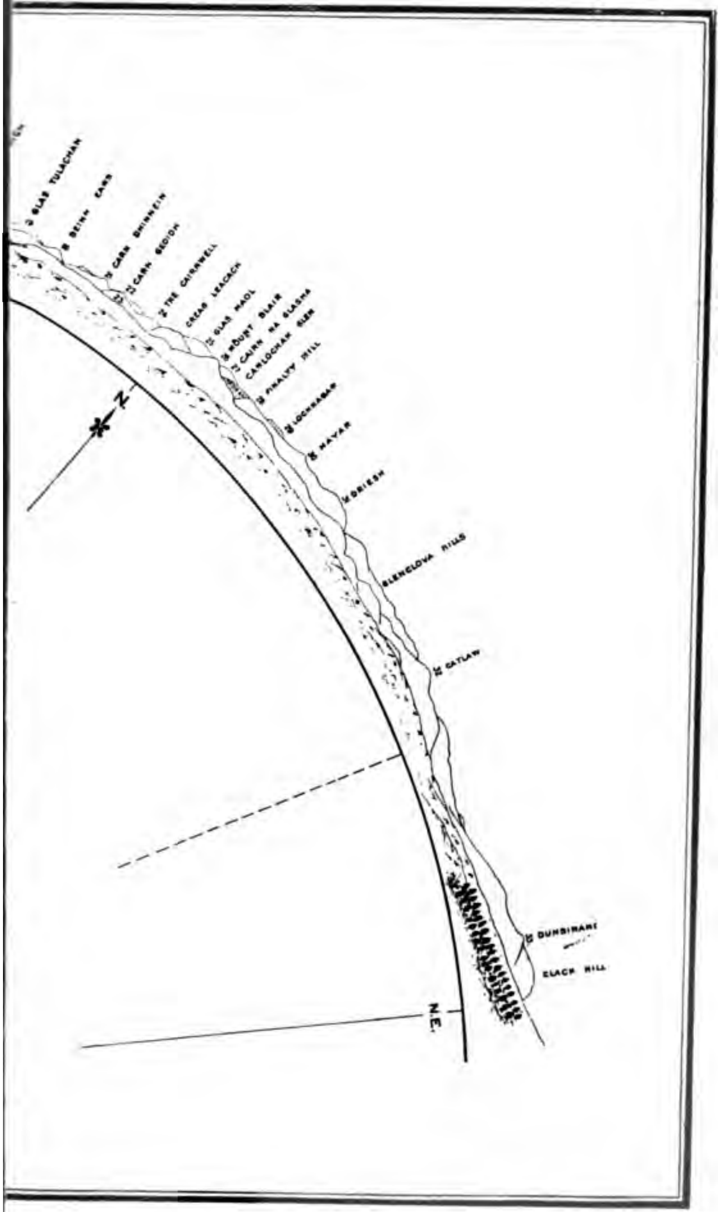
CHAPTER III

OUTLINE OF THE PHYSIOGRAPHY AND GEOLOG OF THE GRAMPIANS AND STRATHMORE

> Sad, indeed, is it to see how men occupy themselves with trivialities, and are indifferent to the grandest phenomena . . . and pass by without a glance that grand epic written by the finger of God upon the strata of the earth.
>
> HERBERT SPENCER.

THE Grampians form an immense mountain mass whic stretches across the more southerly portion of th Highlands of Scotland, and overlooks the Lowlan lying to the south-east. Geographically, the Grampians are usually described as "a chain of mountai extending from Dumbarton or from the Cowal Hil on the west, to the sea at Stonehaven on the east, o to the interior of Aberdeenshire." The great mountain rampart of the Highlands is flanked from wes to east by the band of low country known as th valley of Strathmore, which in its turn is bounde on the south and east by the Campsie, Ochil, an Sidlaw Hills.

A glance at a good topographical map will at onc convey an idea of the general physical characters o the Grampian mountains. Thus the valley system


GLAS TULACHAN
BEINN EARB
CARN BHINNEIN
CARN GEOIDH
THE CAIRNWELL
CREAG LEACACH
GLAS MAOL
MOUNT BLAIR
CAIRN NA GLASHA
CANLOCHAN GLEN
FINALTY HILL
LOCHNAGAR
MAYAR
DRIESH
GLENCLOVA HILLS
CATLAW
DUNSINANE
BLACK HILL
N
N.E.

will be found to fall naturally into two great classes, namely, the longitudinal and the transverse; the former lying parallel to the general north-east and south-west trend of the mountain chain, and the latter crossing the longitudinal valleys in a direction approximately at right angles. As examples of the longitudinal valleys I might cite Glen Dochart, the Valley of Loch Tay, the Tay between Kenmore and Ballinluig, Glen Lyon, the Valley of the Tummel, Loch Rannoch, Loch Earn, the Valley of the Lochlarig river and of Loch Voil, and the Valley of Loch Katrine. As examples of the transverse type I might take the Valleys of the Shee, the Isla, the Ardle, and the Garry, the Valley of Loch Lubnaig with the rivers Balvaig and Teith, and the long wide Valley of Loch Lomond.

In the chapter dealing with the relationships which exist between the scenery and the geology of the Grampians, it will be shown that the orientation of the Highland valleys is intimately associated with their geological structure. In the meantime we may consider the Grampians to be simply a great level plateau, deeply indented with valley systems belonging to the two orders just described.

The use of the term 'plateau' in describing what is generally looked upon as a mountainous country, ought, however, to be explained, and this may best be done by supposing that the reader has taken his stand upon one of the higher summits of the Grampians. On looking around, he will at once be struck by the remarkable uniformity of level to which all the mountains rise; so that, if he could imagine all the intervening valley systems filled up, there would be a great plain rising to a uniform level of about

THE GRAMPIANS SEEN FROM CORSIEHILL, PERTH, AS

Name.	Height in feet.	Guide Line.
1. BEN LEDI	2875	South Spire—St. Mary's Monastery
2. TORLUM	1291	General Station Tower
3. STUC A CHROIN	3189	—
4. BEN VORLICH	3224	Almost over Hamilton House
5. AM BINNEIN	3827	—
6. BEN MORE	3843	Over St. John's Church Steeple
7. CARN CHOIS	2571	Over South end of Wellshill Cemetery
8. BEINN CHAONAIDH	3048	Over North end of do.
9. MEALL REAMHAR	2025	Over North End of Tulloch Works
10. MEALL NAN CAORACH	2044	Do. do.
11. MEALL DEARG	2258	Over South Muirton
12. BIRNAM HILL	1324	Over Gannochy Farm
13. BEINN DEARG	3304	—
14. BEN VRACKIE	2757	Over Whinnymuir Farm
15. BEN-Y-GHLOE—	—	—
(a) Carn Liath	3193	—
(b) Braigh Coire Chruinn Bhalgain	3505	—
(c) Airgiod Bheinn	3250	—
(d) Carn nan Gabhar	3671	—
16. DUCHRAY HILL	1670	—
17. BEINN BHUIRICH	2961	Over Langley Cottage
18. CARN AN RIGH	3377	Over Scone Parish Church
19. GLAS TULACHAN	3445	—
20. BEINN EARB	2610	—
21. CARN BHINNEIN	3006	—
22. CARN GEOIDH	3194	Little to left of Pickstonhill Farm
23. BEINN GULABIN	2641	Do. do.
24. THE CAIRNWELL	3059	Over Pickstonhill Stackyard
25. GLAS MAOL	3502	—
26. MOUNT BLAIR	2441	—
27. CAIRN NA GLASHA	3484	Over Abbey U.F. Church, Scone
28. FINALTY HILL	2954	Over N.E. end of Scone
29. LOCHNAGAR	3786	Midway between Scone and Balgarvie
30. MAYAR	3043	Over Balgarvie Farm
31. DRIESH	3105	—
32. CATLAW	2196	Left of Muirhall Farm
33. DUNSINANE	1012	—

Note.—From the road leading uphill past the Inwickers' Curling Pond in Deuchny Quarry, Inch; Schichallion (3547), to right of Meall Dearg (No. 11 above), and Little Glen Shee; be seen from the top of Kinnoull Hill—point north of Stone Table.

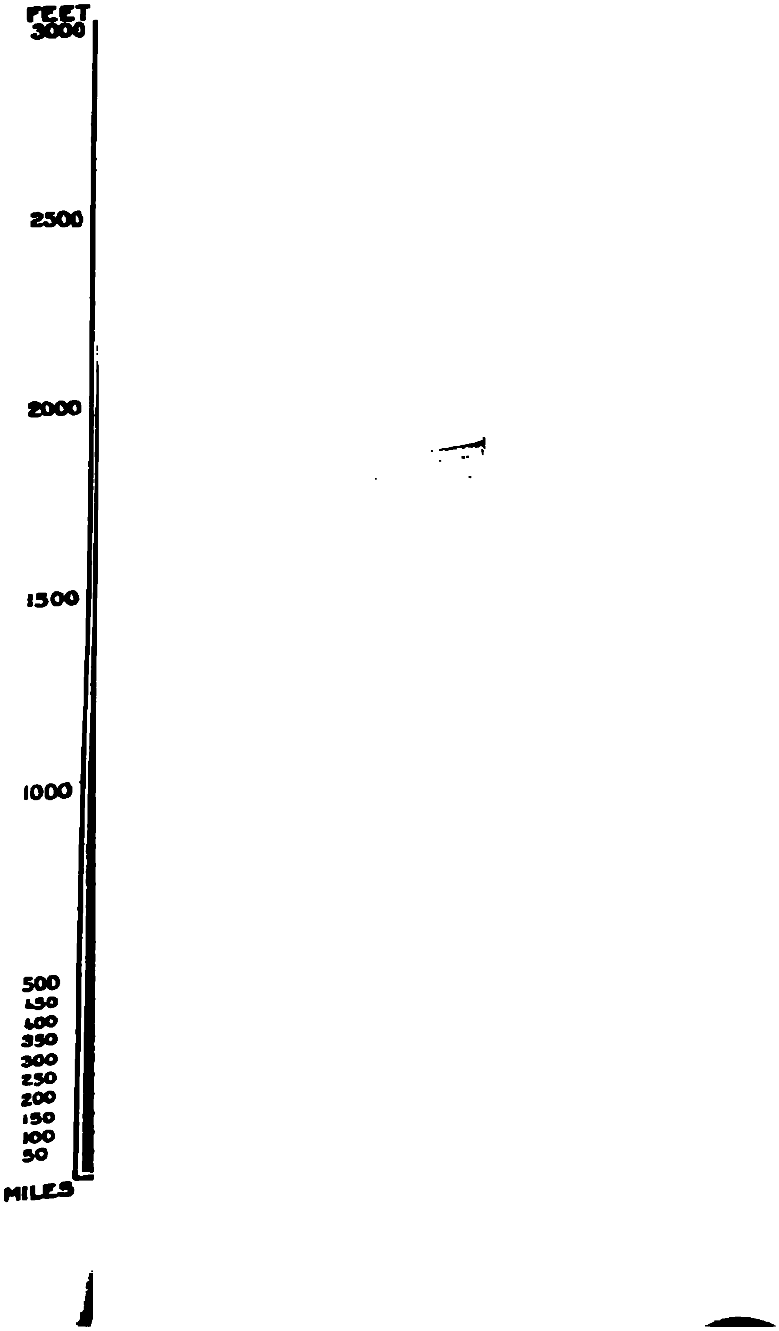
SHOWN IN THE ACCOMPANYING DIAGRAMMATIC CHART.

Distance in miles.	Notes.
36	5 miles N.W. of Callander.
19	Between Crieff and Comrie; sometimes wrongly said to be the highest wood-crowned hill in Scotland.
32	"The Mountain of the Plough," or "The Mountain of the Cloven Hoof"; 1 mile S.E. of Ben Vorlich.
31	"The Mountain of the Big Hillock"; on S. shore of Loch Earn. The highest mountain on the southern side of Strathearn.
44	"The Peaked Mountain," or "The Little Ben"; sometimes called Stobinian. Twin peak of Ben More.
44	"The Great Mountain"; on S. side of Glen Dochart, near Crianlarich. After Ben Lawers, the highest mountain in Perthshire.
21	7 miles N.W. of Crieff, on W. side of Glen Turret.
23	Commonly known as Ben Chonzie; 9 miles N.W. of Crieff. The highest mountain on the northern side of Strathearn.
15	"The Fat Hill"; 3 miles S.E. of Amulree.
15	"The Hill of the Sheep"; 3 miles S.E. of Amulree.
19	"The Red Hill," between Amulree and Aberfeldy; on W. side of Glen Cochill.
12	Famous from the reference in "Macbeth"—"Fear not till Birnam Wood do come to Dunsinane."
38	"The Red Mountain"; from a vein of red stone, said to be a kind of granite; 8 miles N. of Blair Atholl on the N.W. side of Glen Tilt, and near the source of the Bruar Water.
27	"The Spreckled Mountain"; 3 miles N. of Pitlochry.
32	"The Mountain of the Mist"; on S.E. side of Glen Tilt. Four peaks or summits.
—	"The Grey Cairn"; 5 miles N.E. of Blair Atholl.
—	"The Brae of the Round, Bag-shaped Corrie."
—	"The Silver Mountain."
—	"The Cairn of the Goats,"
17	"The Black Craig"; 4 miles N. of Dunkeld; on S. side of Loch Ordie.
29	"The Mountain of Bellowing"; formerly known as Ben Vuroch; 3 miles S.E. of Carn nan Gabhar.
33	"The Hill of the King"; believed to have been named after King Malcolm III. (1058-1093), who is said to have frequently hunted in Atholl.
32	"The Grey Hillocks"; 6 miles N.W. of Spital of Glen Shee.
28	"The Hill of the Roes"; 2 miles W. of Spital of Glen Shee.
32	"The Cairn of the Little Peak"; 4 miles N.W. of Spital of Glen Shee.
33	"The Cairn of the Goose"; 4 miles N. of Spital of Glen Shee.
29	1 mile N. of Spital of Glen Shee.
33	5 miles N. of Spital of Glen Shee, on boundary line between Perthshire and Aberdeenshire. The coach road from Blairgowrie to Braemar runs over its eastern shoulder.
32	"The Grey Bare Hill"; seen just to the left of Mount Blair. The highest summit in Forfarshire. The Counties of Perth, Forfar, and Aberdeen meet on the N.W. side of the hill.
24	W. side of Glenisla; 13 miles N. of Blairgowrie.
33	Seen just to the right of Mount Blair. To this mountain Queen Victoria and Prince Albert made their last hill excursion together in 1861.
31	Just to the west of this hill may be seen the crags of Canlochan Glen, the source of the River Isla.
39	7 miles S. of Balmoral. Celebrated in Byron's poem.
31	At the source of the Prosen Water. Forms part of the southern boundary of Glen Doll.
31	"The Hill of the Blackthorns"; west side of Glen Clova, and part of southern boundary of Glen Doll.
25	6 miles N.W. of Kirriemuir.
7	Site of Macbeth's Castle. See No. 12 above.

the following mountains may also be seen: Ben Lawers (3984), over north end of North Farragon (2559), over Glengar; Cairntoul (4241), to left of Carn an Righ. Some of these may

3000 feet above the sea (see Fig. 6). I shall discuss the origin of the great plateau later; meanwhile I indicate its existence, that the reader may better grasp the true physical character of the ground.

As already stated the Grampians rise to an average elevation of about 3000 feet, though quite a number of peaks exceed this altitude. The following are some of the principal altitudes. Along the Highland frontier we have in Argyllshire, Ben Mhor (2433 feet); in Stirlingshire, Ben Lomond (3192); in Perthshire, Ben Venue (2393 feet), Ben Vane (2685), Ben Ledi (2875), Ben Vorlich (3224), Ben Chonzie (3048). In Argyllshire we have farther, Ben Arthur (2891), Ben Ime (3318), Ben Bhuidhe (3106), Ben Cruachan (3689), Ben Doireann (3523). In Dumbartonshire we have Ben Vane (3004) and Ben Vorlich (3092). In the south-west corner of Perthshire the chief mountains are: Ben Laoigh (3708 feet), Ben Odhar (2948), Ben More (3843), Am Binnein (3827). On the ridge that separates Loch Tay and Glen Lyon are: Ben Lawers (3984 feet), Meall Garbh (3661), Meall nan Tarmachan (3421); further east, and in the same line of bearing, Farragon Hill (2559) and Ben Vrackie (2757). In the north-east of the county, and along the boundary of Atholl, are: Carn an Fhidhleir (3276), An Sgarsoch (3300), Glas Mheall Mor (3037), Carn Bhinnein (3006), Cairnwell (3059), Ben-y-Ghloe (3671), and Ben Vuroch (2961). The principal mountains on the ridge that separates the River Lyon and Loch Rannoch are: Schichallion (3547 feet), Carn Gorm (3370), Carn Mairg (3419). North of Loch Lydoch and Loch Rannoch, Ben Alder (3757), Carn Dearg (3084 feet), Sgor Gaibhre (3128), Ben Phar-


FEET
2000
1500
MILES

lagain (2836); and in the north-west of Perthshire and the neighbourhood of Loch Lyon, Ben Creachan (3540 feet), Ben Heasgarnich (3530), Creag Mhor (3387), Meall Ghaordie (3407), and Ben Vannoch (3125).

All these mountains are formed of the Highland metamorphic rocks, and lie to the north-west of the great boundary fault which separates the younger Palaeozoic rocks of the Lowlands from the much older crystalline schists of the Highlands. This line is therefore both a geological and a geographical line. It can be traced across the whole of Scotland from sea to sea; it passes through Arran, Bute, and Loch Lomond, and enters Perthshire near Aberfoyle, striking north-eastwards by Callander, Comrie, Crieff, Birnam, and the Bridge of Cally. Here and there such foot-hills as Uamh Bheag (2168 feet) and Uamh Mhor (2179 feet) roll up to meet the great mass of the Grampians, but when viewed from such an eminence as Kinnoull Hill, near Perth, the Highland mountains seem to spring from the plain like a great wall or rampart.

The diagram facing page 60 shows the profile of the Grampians as seen from Corsiehill, Perth. It stretches from Ben Ledi in the west to the Glen Clova Hills in the east, and illustrates in a striking manner the general appearance of the Grampians as viewed from the Ochil or Sidlaw Hills.

The remaining belts of high ground, namely the Ochil and the Sidlaw Hills, are separated from the Grampians by the broad valley of Strathmore. The Ochils lie in the south of Perthshire, and stretch from the Forth near Stirling to the neighbourhood of Perth.

Some of the principal heights are as follows: Ben Cleuch (2363), King's Seat Hill (2111), Whitewisp Hill (2110), Mickle Corum (1955), Blairdenon Hill (2072), Core Hill (1780), East Bow Hill (1562), Carlowrie Hill (1552), Muckle Law (1306), Rossie Law (1064), Skymore Hill (1302), Cock Law (1337), and Castle Law (1028). The Sidlaw Hills on the north side of the Firth of Tay separate Strathmore from the Carse of Gowrie, and they may be considered as simply a northern prolongation or branch of the Ochils. The principal altitudes taken in order from south to north are: Kinfauns Hill (555 feet), Kinnoull Hill (729), Evelick or Pole Hill (944), Beal Hill (849), Black Hill (1182), Dunsinane Hill (1012), King's Seat (1235), Blacklaw Hill (929), Balo Hill (1029), and Kinpurney Hill (1134).

The view shown on Fig. 6 will give the reader a very good idea of the general character of the Highland tableland. The observer is standing upon the phyllites of the Upper Argillaceous Zone, a group of schists which constitute the summit of Ben Lawers, and which will be dealt with in more detail in Chapter V. To the left is seen Beinn Ghlas, composed of rocks belonging to the same zone. Behind, and partly hidden by the southern ridge of Beinn Ghlas, we get a gimpse of Loch Tay. Beinn Ghlas is connected with Meall Corranaich, which slopes to the north, while Meall nan Tarmachan occupies the middle of the panorama. The chief horizon summits visible in the picture, reaching in succession south to north, are Ben Ledi, Ben Vane, Ben Lomond, Stob a' Choin, Stob Coire an Lochan, Am Binnein, Cruach Ardran, Ben More. Then comes the dip of the

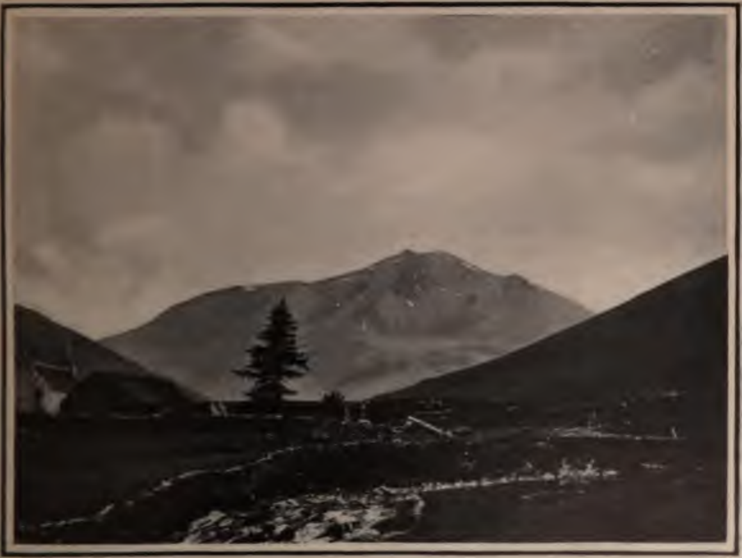


FIG. 7.—Ben Laoigh, from Coninish (the source of the Tay).

Photo. by J. W. REOCH.

Dochart, and first the flat top of Meall Chuirn, then Beinn Bhuidhe (Bui), Beinn Dubh-chraige, Beinn Oss, Beinn Laoigh (Lui), the source of the Tay, Beinn Chaluim, Creag Mhor, Beinn Heasgarnich, Beinn Doireann, and Beinn an Dothaidh. Behind Creag Mhor the twin peaks of Beinn Cruachan are visible in the negative, but too faint for reproduction. This photograph will enable us to form a conception of the general physiographical aspect of the Grampian tableland. It may also be mentioned here that the area depicted in the foreground lies along the line of a great structural axis in the schists which has played a most important part in the geological history of the Highlands.

The view shown in Fig. 40 is also taken from the summit of Ben Lawers, but is looking in an opposite direction from that just described. To the left of the picture is seen the conical summit of An Stuc, and behind it the ridge of Meall Garbh rising above Lochan a' Chait, and which trending eastwards rises again in Meall Gruaidh. Beyond is seen Kenmore and the east end of Loch Tay, the high ground south of the loch beginning in Drummond Hill is topped by Beinn Bhreac and Meall a' Choire Chreagaich. In the middle of the view, behind the dark undulating mountain tops overlooking Glen Lyon, are seen Schichallion and Carn Mairg. This photograph, like that already described, will enable the reader to gain some idea of the scenery along the great tectonic axis of folding as it is prolonged north-eastwards into the Aberdeenshire Highlands.

The view shown in Fig. 93, vol. ii., is taken from the south side of Loch Tay, and shows the loch in the middle foreground. The principal peaks seen in the background, and reaching from left to right, are Meall Ghaordie, Creag na Caillich, Beinn nan Eachan, Meall Garbh, Meall nan Tarmachan, Meall Corranaich, and Beinn Ghlas with the summit of Ben Lawers appearing over it. Up to about the 2000 feet contour line this ridge consists of garnetiferous quartz- and mica-schists. Above this, and forming the summit of the mountains, we have the different schist zones which constitute our Upper Argillaceous Zone. These mountains, as has already been pointed out, are situated upon the great backbone or axial line of folding in the Highlands, from which the mountain-building forces have pushed outwards towards the north-west and south-east. The structure of this ridge will be given in considerable detail in a later chapter.

By far the larger part of the area under consideration is drained by the Tay and its tributaries, the south-western portion being drained by the Forth, which also forms the boundary line of Perthshire for a considerable distance.

The Tay rises in a corrie on the north side of Ben Laoigh in the confines of Argyllshire and Perthshire, at an altitude of almost exactly 3000 feet above sea level. After having travelled a distance of eleven miles it has descended to an elevation of only 500 feet, and down to this point has been known as the Fillan Water (see Figs. 7 and 8). Here it enters Loch Dochart, passes through it and Loch Iubhair, and on emerging from that Loch it has a course of 14½ miles, when it is known as the Dochart, falling eventually into Loch Tay at Killin (see Fig. 9). If we include the Fillan and Dochart as part of the river

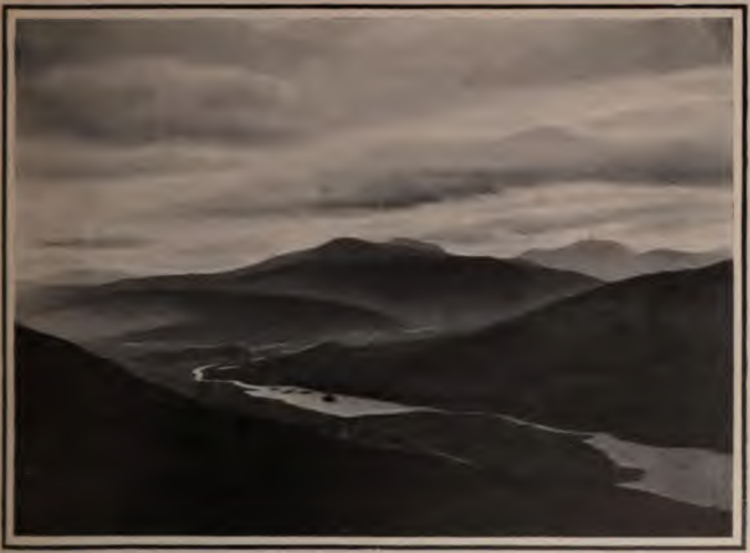


FIG. 8.—Looking up Strathfillan to Ben Laoigh, from north side of Ben More.

Photo. by J. W. REOCH.

Tay, it gives it a total length of about 117 miles, draining an area of nearly 2000 square miles. The chief distances may be thus summarised:

Source to Loch Tay, - - -	25 miles
Head of Loch to Kenmore, - -	14½ "
Kenmore to Junction with Tummel,-	15½ "
Junction with Tummel to Perth Bridge,	31 "
Perth to mouth, - - - -	31 "
	117

After leaving Loch Dochart the gradient of the river, or its fall in elevation, becomes comparatively slight, the surface of Loch Tay being 350 feet above sea level. At the junction with the Tummel the height is 200 feet, and at a point about a mile above Perth, elevation may be said to disappear, for the Tay has become a tidal river. Twice in its course the Tay changes its direction in a very marked manner, giving rise to three distinct divisions. Starting from the source its direction is north-easterly until it is joined by the Tummel. There it turns almost at right angles, and assumes a direction, mainly south-easterly, across the vale of Strathmore, until it reaches Perth. It there takes another sharp bend, flowing nearly east till it enters the sea. Its course may be described as a rough parabolic curve through the centre of Perthshire.

After leaving Loch Tay the river receives the following tributaries. A few miles below Kenmore it is joined on its left bank by the waters of the Lyon, which rise in Loch Lyon. Beyond Aberfeldy it is joined on the left bank, near Ballinluig Station, by the Tummel from the Moor of Rannoch. The Tummel drains Loch Lydoch, Loch Ericht, Loch

Rannoch, and Loch Tummel, and also brings with it the waters of the Garry from Loch Garry. Near Dunkeld the river receives on its right bank the Bran, which drains Loch Freuchie, and at Kinclaven Castle on its left bank it receives the Isla, which brings with it the Shee, the Ardle, and the Ericht. A few miles above Perth it receives on its right bank the river Almond, which rises to the south of Loch Tay and joins the main stream opposite Scone Palace, while below Perth and to the west of Newburgh, it receives the Earn on its right bank, which is its last tributary of any importance.

The sudden changes of direction in the course of the Tay are notable. The western portion of the Perthshire Highlands is trenched by a series of longitudinal valleys running more or less east and west. These are the valleys of the Earn, the Almond, the Bran, the Tay, and the Tummel. These valleys are terminated at their eastern extremities by a great transverse valley, running north-west and south-east and cutting them off nearly at right angles. Through this valley flows the Garry, and, as it passes on, it gathers up the waters of each of the longitudinal valleys in turn, carrying them southwards in a combined stream. This transverse valley terminates at Dunkeld, where the river emerges from the Highlands, but although it takes advantage of its newly found freedom to assume a more winding track, its main direction continues the same until it reaches Perth. Here, however, it meets with a formidable barrier in the Sidlaw range, and although it has succeeded in forcing a passage for itself between the hills of Kinnoull and Moncrieff, the

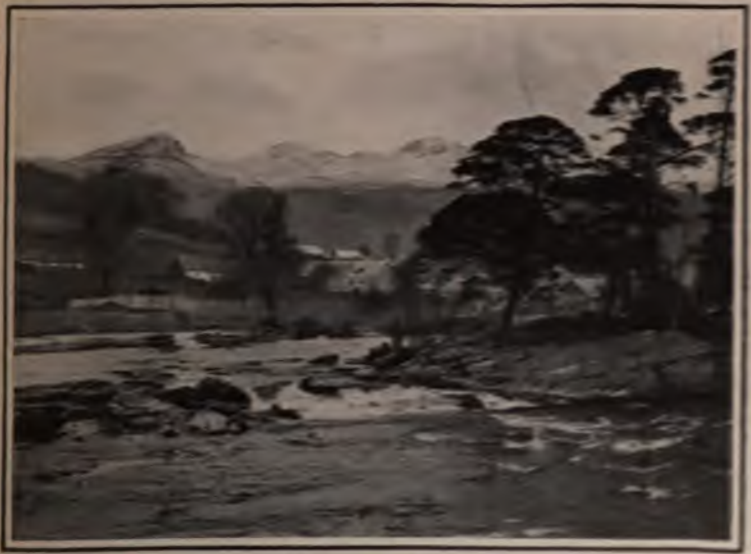


Fig. 9.—The Killin Hills, from the Dochart.

Photo. by J. W. Rench.

achievement has been at the expense of shortening its course, because the effort has effectually bent its direction eastward along the shortest possible route to the sea (see diagram facing page 64).

The south-western portion of the area under consideration is drained by the River Forth and its tributaries, which for a considerable distance forms the southern boundary of Perthshire. The Avondhu and the Duchray, which are the headwaters of the Forth, rise on the east side of Ben Lomond at an altitude of over 2000 feet. These streams run parallel to one another in a south-east direction, the Duchray water forming the boundary between Perthshire and Stirlingshire, and the Avondhu flowing through Loch Chon and Loch Ard, the streams uniting to form the Forth proper about a mile to the west of the Clachan of Aberfoyle (see Fig. 63). East of this the Forth receives the following tributaries on its left or Perthshire bank: the Goodie, the Teith, the Allan, and the Devon. The Teith is formed by two streams, one of which descends from the south side of Ben a' Chroin and flows through Loch Voil and Loch Lubnaig, being successively known as the Balvaig and Leny: the other flows from Loch Katrine, through Loch Achray and Loch Venachar, and unites with the Leny at Callander. The Falloch rises on the north side of Ben a' Chroin and enters Loch Lomond at its head.

Another characteristic topographical feature of this region is the existence of numerous fresh-water lakes, such as Loch Tay, Loch Earn, Loch Rannoch, Loch Katrine, and others. These lakes occupy deep basin-like hollows, either in the longitudinal or in the transverse valley systems. As has long ago been pointed out, these basins do not correspond to great fractures in the earth's crust, but have been excavated from the solid rock, most probably by glacier ice (see Fig. 8).

Viewed from a purely aesthetic standpoint, the scenery of the Grampians and Strathmore cannot be surpassed by anything in this country. It affords examples of all types of inland scenery, much of which has been rendered classic by important events in Scottish history. Mountains, lakes, rivers, cascades, woods, and rocks supply the elements that combine to make up all that is grand and beautiful in every landscape (see Figs. 10, 11). In the course of a walk of a few miles one may pass from a deep ravine, or rugged Alpine glen, into a rich and open valley which partakes of the cultivated beauty of the lowlands, and in the centre of which lie embosomed the waters of a great lake. Or one may follow the wanderings of a great river from its source among the mountains, whence, as a torrent, and with a wild mountain cry, it precipitates itself over ledges of rock to become lost in the black moor beneath, but which, after a course of many miles, finds itself meandering through a spacious vale, or widespread wooded plain. Behind, the fading tints of the blue mountains as they rear themselves like a huge rampart against the evening sky, may just be discerned; and in front gleams the placid bosom of the ocean, towards which the river is gradually transporting, grain by grain, and cliff by cliff, the great mountain masses amongst which it ha its birth (see Fig. 7).

From a geological standpoint the region under consideration presents an almost unique field for the stu of physical geology, embracing as it does such

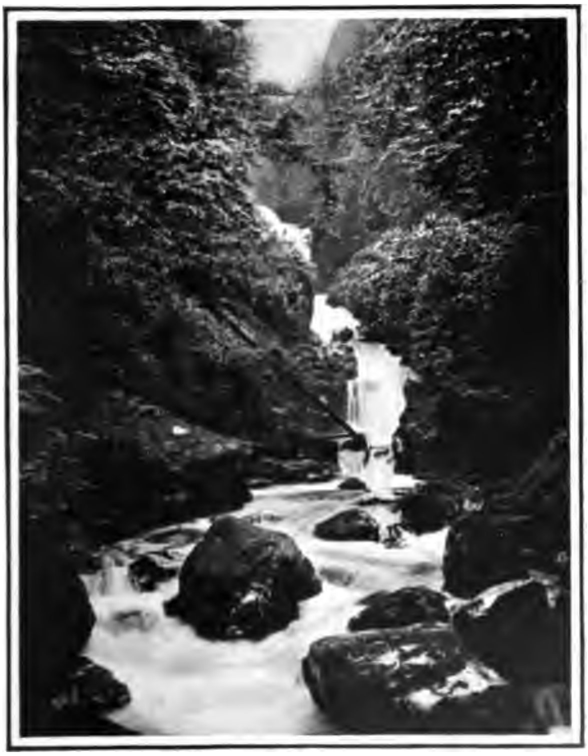


FIG. 10.—Lower Fall of Moness, Aberfeldy.

Photo. by J. S. GRANT.

THE [illegible] YORK
PUBLIC LIBRARY

and extent of rock formations. No attempt can be made to enter into anything like a detailed account of the geology of the area, as it would be almost impossible to compress such a long story into small compass. Nevertheless, we hope to be able to bring out some of the more salient features of this wonderfully rich and varied geological field, and to sketch in some of the principal events which have taken place in its long and interesting history, as we find the record of them written upon the rocks.

Geographically the mainland of Scotland may be divided into three great divisions—the Highlands, the Southern Uplands, and the Midland Valley—each being characterised by a scenic aspect of its own, which, as we shall see, is intimately connected with its geological structure. Further, it may be pointed out that the scenery, and ultimately the land and soil upon which we live, have been the principal factors in moulding our character as a nation; and for this reason alone, if for no other, Scotsmen ought to take an intelligent interest in the structure of their native land. How truly, for instance, it may be said of Glasgow, our great commercial capital, that it is a "dark, sea-born city." Had the great estuary of the Clyde not been designed and sculptured out in bygone geological ages, and had the immense stores of iron and coal not been laid up in the rocks beneath, this great city could never have existed where it now stands; nor is it likely that a great genius like Watt, whose invention was to knit together the ends of the earth, would ever have arisen except in a country which seems to have been specially designed to call forth and foster such powers.

In a similar fashion our intellectual and spiritual life may be considered to be, to a great extent, the product of the scenery that surrounds us. Had it not been for the existence of thick masses of grit, intercalated in the Highland schists, we could not have had that wild and rugged scenery which is characteristic of Ben Ledi, Ben Vorlich, Ben A'an, Ben Venue, Loch Katrine, and the surrounding lake district, which inspired Sir Walter Scott, and round which he has thrown a halo of romance, which has made that part of Scotland a veritable Mecca for the English-speaking race. Again, where but amid the lonely mountains of the Scottish Highlands could we have expected the dreamy, ghost-like strains of Ossian to have found their birth; where else could they have been nursed except beneath the shadows of great mountains and amid the murmurings of pine forests? Numerous other examples might be cited of the bearing and influence of the geological structure of the country upon its national history, but it is unnecessary that they should be multiplied here. Still, we must not pass over our greatest national feature, namely, our independence, and the manner in which we have preserved it against all assailants. A glance at a geological map will show how much we have been dependent upon the physical configuration of our country for this success; for the map will at once reveal that the different rocks which enter into the formation of our country are arranged in more or less parallel bands, some of them rising into hilly or mountainous masses, while others sink into plains or valleys, thus forming a series of ramparts and trenches, from which our southern invaders more than once forced us, step by step, only to find us return again. Behind all, we had the grand rampart of the Highlands

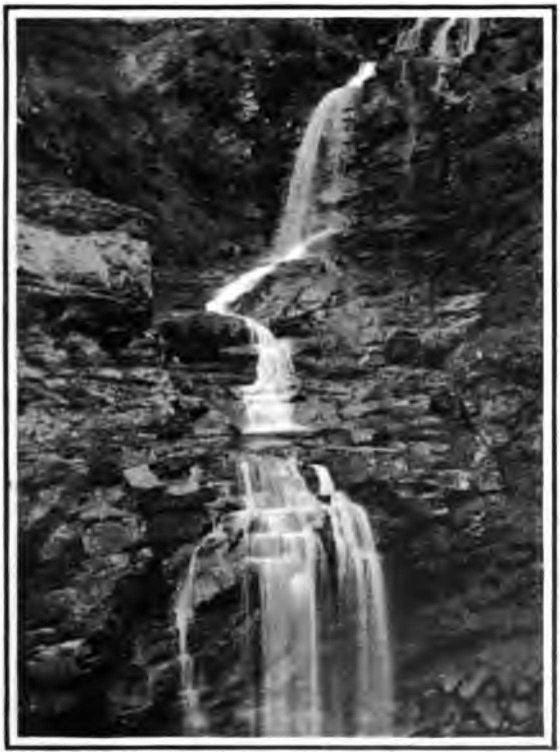


FIG. 11.—Falls of Balnaguard, near Logierait.

Photo. by J. S. GRANT.

LIBRARY

with its great mountains, deep valleys, and sea lochs. Into these even the Roman Eagle could not penetrate, the conquerors having to content themselves by building walls and towers to fence off the fierce tribes. There cannot be the least doubt, then, that we owe much of our national character to that peculiar geological structure which has shut out this mountain-land from all intercourse with our southern neighbours (see Frontispiece, vol. ii.).

The great boundary fault, to which we have already referred, runs across Scotland in a diagonal direction and divides the country into two portions—the Highlands and the Lowlands. This is a geological as well as a geographical line of demarcation, and separates the crystalline schists of the Highlands from the younger Palaeozoic rocks of the Lowlands (see Fig. 12).

The rocks of the Grampian mountains are metamorphic—that is, they were, in the majority of instances at least, originally laid down as sedimentary deposits, but have subsequently been altered, both by the great folding and plication to which they have been subjected, and by the intrusion of great bosses of igneous rock. These metamorphic rocks show many different stages in the process of alteration. In some of the siliceous members the rounded granules of quartz are still recognizable, though often transfused into a siliceous cement or matrix. Some of the grits and conglomerates bear still more conclusive evidence of their clastic origin (see Figs. 17 and 18).

It has long been recognized that the metamorphic rocks of the Highlands traverse that area in bands or zones, having a general north-east and south-west trend, roughly parallel with the great boundary fault. The

Lower Argillaceous Zone abuts against the younger Old Red Sandstone rocks to the south, but is separated from them by the boundary fault. Outcropping at the base of the schist series of the southern Highlands, it stretches across their frontier from sea to sea. In Perthshire it may be seen at Birnam, Logiealmond, Comrie, Callander, and Aberfoyle (see Figs. 15 and 16).

Immediately to the north-west of this Lower Argillaceous Zone another broad band of rocks, with a more or less well-developed foliation, occurs, which, because of the predominance in it of coarsely fragmental material, has been termed the Lower Arenaceous Zone. The rocks of this group vary from exceedingly fine-grained light and dark greywackes, to massive grits with pebbles often an inch in diameter. This zone may be traced through Ben Venue, Ben Vorlich, and Ben Ledi, and gives rise to the characteristic scenery of the Trossachs (see Figs. 53 and 55).

Above the group just described occurs one of the best marked zones of all the schists seen in the southern Highlands—that known as the Loch Tay Limestone. It has been traced from shore to shore across the whole breadth of the southern Highlands. Upon this horizon occur massive beds of sheared basic igneous rocks, which accompany the limestone in a remarkable manner from east to west across the whole of the Highlands (see Figs. 30 and 31).

Above the Loch Tay Limestone there comes a band of mica-schists and quartz-schists, characterised by the abundance of garnets which they contain. This group of strata has been named the Garnetiferous Schist Zone, and forms a tolerably well marked horizon immediately above the Loch Tay Limestone (see Figs. 22 and 23).

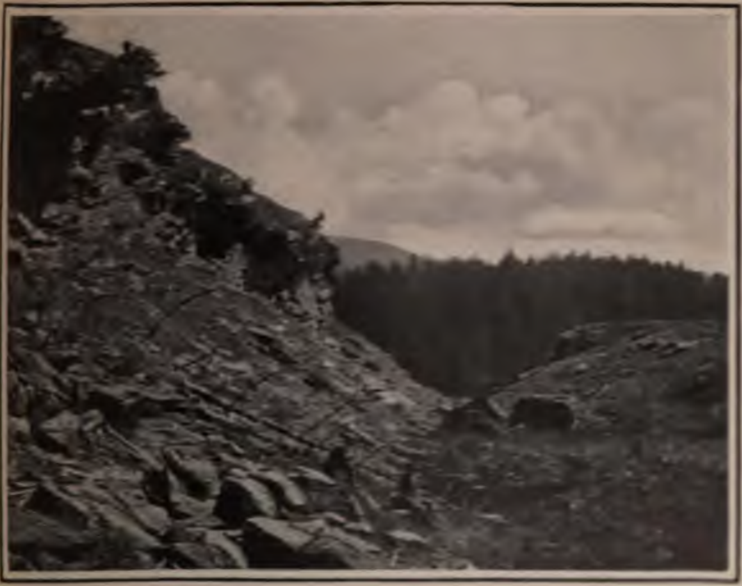


FIG. 12.—On the line of the Boundary Fault, Craigie Barns, Dunkeld.

Photo. by H. COATES.

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS

A well-marked group of phyllites, schistose-quartzites, and graphite-schists—the Upper Argillaceous Zone—succeeds this. The zone is well seen in the mountains north of Loch Tay. At Tyndrum it is faulted against the central Highland quartzites, whence it runs north-east towards Glen Lyon (see Figs. 25 and 26).

Succeeding the Upper Argillaceous Zone, and covering the greater part of the north and north-west of Perthshire, there is a group of quartzites and limestones, named the Upper Arenaceous Zone, because of the predominance in it of quartzites. It can be seen in the neighbourhood of Blair Atholl, the limestones being well exposed in Glen Tilt, whence they can be traced westwards through Schichallion, Glen Lyon, and the Black Mount.

All these schists have been thrown into great folds, whose structure will be discussed in a future chapter.

Along the Highland frontier, and immediately to the north of the great line of fault, the officers of the Geological Survey have mapped a narrow belt of carbonaceous shales, schists, and cherts (see Figs. 58, 59, and 62), the latter containing forms resembling radiolarian tests. These, they consider, may be of Arenig age. They appear to have been wedged in between the Highland schists and the Old Red Sandstone, and can be traced at intervals right across the country.

The whole problem of the relationship of this belt of rocks to the crystalline schists of the Highlands is at present in a very unsettled condition; and though they undoubtedly present a striking resemblance to the Arenig rocks of the Southern Uplands, yet, in the entire absence of recognizable fossils, it is perhaps as well not to press the actual identity of the formations. Could their Arenig age be established, it would modify to a considerable extent our present conception of the history of the Grampian mountain chain; but it would be entirely useless to discuss this question in the present unsettled state of the subject.

The Lower Old Red Sandstone rocks abut against the crystalline schists of the Highlands, and are usually separated from them by the boundary fault. Here and there, as at Crieff, outliers of the Old Red Sandstone still rest upon the schists (see Fig. 7, vol. ii.).

Along the southern margin of the Highlands, and bordering on the schists, we find a massive series of conglomerates thrown down against the schists at high angles (see Figs. 2, 14, vol. ii.). Proceeding towards the south-east we find that these basal conglomerates pass into fine beds of shale and sandstone, which are bent into a synclinal trough. In the upper members of these sandstones there is a well-marked horizon exposed along a line running from Rosemount, near Blairgowrie, by Murthly, Logiealmond, and Callander, to Balmaha, on the shores of Loch Lomond, where the strata are strongly charged with vegetable matter, principally the decorticated remains of *Psilophyton* and *Arthrostigma* (see Fig. 5, vol. ii.).

The geological structure of the synclinal trough of Lower Old Red Sandstone rocks is well seen in a section taken from the heads of the Kelty and Ruchill Waters, through Uamh Mhor and Uamh Bheag, to Sheriffmuir. The whole section forms a deep trough, whose northern limb, seen in the Kelty and Ruchill Waters, consists of massive beds of conglomerate, and shales, with interbedded andesites, lying in an almost vertical position against the crystalline rocks of the Highlands. These conglomerates near the summit of the synclinal trough pass upwards into the axial beds of Uamh Mhor. From this point southwards to Sheriffmuir the series is a descending one, forming the southern limb of the syncline, and repeating the former beds in a finer state of sedimentation. Ultimately the whole series passes downwards into the volcanic zone of the Ochils.

On the south side of this syncline the lowest members of the Old Red Sandstone are seen near the Yetts of Muckart, where they consist of very coarse agglomerates and lava flows. Above these there is a considerable thickness of andesites with intercalated agglomerate, and these again give place, in ascending order, to beds of tuff, which eventually pass upwards into rocks of sedimentary origin. It has been estimated that the volcanic rocks seen in the northern limb of the anticline of the Ochils reach a thickness of over 6000 feet (see Fig. 35, vol. ii.). Near the boundary fault the conglomerates are generally inclined at high angles, and in some cases are actually inverted (see Fig. 2, vol. ii.).

As we pass south-eastwards from the boundary fault the angle of dip gradually lessens, till the strata become horizontal. It is also worthy of notice that as we recede from the Highland boundary the strata gradually become finer, passing from massive conglomerates through grits and pebbly sandstones, into fine-grained sandstones and shales. It has been inferred from the occurrence of metamorphic rocks in the conglomerates of Uamh Mhor that they have been derived from areas lying considerably to the north of the boundary fault, and that the crest of the Grampian Chain must have been exposed when these deposits were being accum

Passing now to the rocks of the Upper Old Red Sandstone of the region, it has been found that they always rest unconformably upon the Lower Old Red Sandstone, and pass up conformably into the Calciferous Sandstones of the Carboniferous system (see Figs. 12, 13, vol. ii.). In Perthshire the Upper Old Red Sandstones are seen only along the Carse of Gowrie, and have there been preserved in rather a remarkable manner. They have been carried down into the heart of the Lower Old Red Sandstone volcanic rocks, between two powerful faults, and having thereby escaped the general denudation which has swept away the rest of the Upper Old Red Sandstone, they have thus been preserved. In the neighbourhood of Forgandenny and Bridge of Earn the basement beds are seen to rest unconformably upon the older volcanic rocks; further to the east they are brought into conjunction with these volcanic rocks. The Upper Old Red Sandstones of the district consist mainly of marls and red sandstones, and in the neighbourhood of Clashbennie they have yielded finely preserved specimens of the characteristic fishes of this formation.

The only representative of the Carboniferous formation found north of the Ochils is a small patch exposed in the neighbourhood of Bridge of Earn. The strata belong to the Cement-stone series lying at the base of the Carboniferous system, and consist of beds of blue-clay sandstone with calcareous bands. Like the Cement-stone group south of the Ochils, these beds are almost destitute of fossils. Specimens of *Estheria*, and a few plant remains, have been found in the blue clays. This outlier of Lower Carboniferous rocks is of great interest, as it serves to [illegible] former extension of that formation over Perthshire, from which it has now been almost entirely removed by denudation (see Fig. 13, vol. ii.).

Everywhere throughout the country ample traces may be seen of the glacial conditions which obtained in Scotland in (geologically speaking) comparatively recent times. Ice-worn surfaces can be observed everywhere, and are abundant even on the highest summits of the Ochils and the Sidlaws (see Fig. 55, vol. ii.). These are almost invariably seen to be rounded, smoothed, and grooved with fine lines, indicating the direction in which the body of ice has moved. The peaks of some of the mountains of the Highlands show similar striations, and the presence of *roches moutonnées* indicates the existence and work of the later glaciers (see Fig. 54, vol. ii.).

Overlying these striated rock-surfaces comes the Boulder Clay, often seen in great mass in the Lowland division of the region. It consists of a thick tenacious clay, plentifully charged with boulders, large and small, huddled together without any apparent arrangement, and striated in the direction of their longer axes (see Fig. 62, vol. ii.).

The general trend of the ice movement along the Highland frontier is from the N.W. to the S.E. On the confines of Stirlingshire and Dumbartonshire the trend is N. and S. Upon reaching the Lowlands it appears to have veered still more towards the E., and, after crossing Strathmore, the Ochil and Sidlaw ranges appear to have deflected it still further towards the north. The effects of this glaciation are well shown on the frontispiece.

In the Highlands, numerous traces can be seen of the later glaciers, their presence being indicated by the abundant distribution of moraine matter. Magnificent examples of these moraines can be seen in the valley of the Dochart near Killin, on the banks of Loch Katrine, between Stronachlachar and Loch Lomond, at the head of Glen Garry, and on the col between Glen Garry and Glen Truim. The moraines at the head of Glen Turret are shown in Fig. 64, vol. ii.

Travelled boulders occur plentifully all over the region, the Ben Ledi and Ben Vorlich grits and certain of the later intrusive igneous rocks of the Highlands having supplied the materials for boulders that have been widely distributed by the ice. The principal period of dispersion of these boulders must, of course, have been during the maximum period of cold, and the direction in which they have travelled corresponds with the ice markings on the rocks beneath. A notable example of these travelled boulders is the huge block of Highland schist locally known as "Samson's putting-stone" (see Fig. 60, vol. ii.), which is situated on the rocks of Lower Old Red Sandstone age which form the southern acclivity of Ben Ledi, and overlooks the road between Callander and the Trossachs, near Coilantogle Ford. Numerous other examples might be cited, but this subject will be more fully treated in a subsequent chapter.

Arctic shell beds occur in the finely laminated brick clays which overlie the Boulder Clay, and indicate a considerable submergence during the later part of the glacial period. These beds frequently show crumpling, and the presence of boulders in the clays points to the existence of floating ice in the seas and estuaries during the deposition of the clays and gravels. The shells which have been found in these deposits belong to arctic or sub-arctic species, which are no longer found living in the adjacent seas, but exist in those of more northern latitudes off the coasts of Greenland, Iceland, and Spitzbergen. These fossiliferous clay beds occur both in the Carse of Stirling and the Carse of Gowrie. In the latter locality some fine specimens have been collected near the brickworks at Errol.

In the Carse of Gowrie and the Carse of Stirling the lines of former sea levels can be distinctly traced. The 100-feet beach forming the upper terrace can be seen at Bridge of Allan, from which point it stretches as far as Dollar. It can also be recognized in the Valleys of the Tay and the Earn below Perth; while the Carse of Stirling and the Carse of Gowrie mark the level of the 50-feet beach.

Throughout the whole of the metamorphic rocks of the Grampians we find intrusions of igneous rocks, some of which are older and some later in time than the movements which plicated the schists into their present positions. In certain instances these igneous rocks have been foliated, thus showing that they are of different ages, and that the earlier intrusions took place before the crustal movements which plicated the schists had entirely ceased. Examples of granitic intrusions are to be found in Glen Tilt, and in the neighbourhood of Loch Rannoch and Loch Ericht.

One of the most striking features of these later intrusive masses, and one which has been recognized for a considerable time, is the association, in the same plutonic mass, of rocks of widely different petrological types. Thus at Carn Chois in Glen Lednock a granite and diorite are found in intimate association with one another; at Tomnadashan, on the south side of Loch Tay, a similar relation is seen to exist between a granite and mica-diorite. An interesting paper by Messrs. J. R. Dakyns and J. J. H. Teall, published in the *Quarterly Journal* of the Geological Society for the year 1892, on a somewhat similar plutonic complex near the head of Loch Fyne, shows that in this area the rocks appear to graduate from granite, through an intermediate series, into rocks of an ultrabasic type, and that they cannot be looked upon as indicating distinct and separate intrusions; but, on the contrary, they prove that these various types have been segregated out from the same magma.

Dykes and sheets of quartz-felsite occur everywhere intruded among the metamorphic rocks. Both modes of occurrence can be seen in the region lying between Loch Tay and the Highland border. Dykes of intermediate igneous rocks are also plentifully developed in the Highland area.

Numerous dykes of dolerite cross the region from east to west. Some of these are supposed to be of Tertiary age, and are connected with the volcanic rocks of the Hebrides (see Fig. 41, vol. ii.), while sills of dolerite of Carboniferous age occur on the confines of Perthshire and Stirlingshire.

If the reader would take in at a single glance some of the more salient features of the physiography and geology of the Grampians and Strathmore, let him betake himself to the summit of one of the foot-hills that rise behind the village of Callander; and for this purpose we shall suppose that we stand upon the summit of Tom Dubh, which rises above the valley of the Kelty Water.

For a considerable distance above the Bracklinn Falls the skeleton framework of the glen is laid bare on the sides of the stream, and the thick beds of conglomerate, which stand in a vertical position, present a series of broken edges which run along the summit of the hill and dip like huge ribs into the valley below. Such a section as this gives at one glance a profound insight into those mighty forces which have been at work in the building of our country; and no matter what theory we may take up to account for the phenomena which it exhibits, we shall find that it leads eventually to some inscrutable mystery. Some of the first steps are plain and clear; we can see that the conglomerate is an aqueous deposit, and that it must at one time have buried the Highlands to the depth of many thousands of feet. We can also see that great terrestrial movements have taken place, by which this great pile of sediments has been bent inwards and thrust against the Highlands. But when we pursue our inquiries just a stage further we find ourselves beset before and behind by such difficult questions as: Was it a sea or a lake in which these deposits were accumulated? Are they of marine or of freshwater origin? Accept the freshwater view, then the enormous thickness of the rocks, and their stratigraphical and palaeontological elements, present insuperable difficulties to this interpretation. On the other hand, if we say they are marine, then their paucity in organic remains becomes a serious obstacle. From this section we turn with a feeling of relief and look across the valley. To the right a ridge of crags runs round the mountain side with an ever-increasing steepness, till it passes into the crags which overhang the town of Callander. These present exactly the same geological features as are seen in Tom Dubh, but nature has thrown an earth-veil of vegetation across them, hiding as it were the structural anatomy of the mountains. In the distant west the sun is slowly sinking behind the mountain peaks that guard the Silver Strand. A troop of filmy clouds still floating across the summits of Ben Venue and Ben A'an breaks up the rays of the dying sun, which ever and anon casts a few fitful beams upon the waters of Loch Venachar. To the right, Ben Ledi, the mount Olympus of a forgotten race, rises ridge upon ridge to the summit, upon which here and there still linger, in the deeper hollows, patches of the winter's snow. To the left, the eye can just detect, against the lighter background of the sky, the outlines of Stirling Castle and the Wallace monument perched upon a great intrusive sill of dolerite, which sill has played a very important part in Scottish history. Behind us phantom-like exhalations of vapour swim along the higher valleys, or mount the rugged sides of Stuc a' Chroin and Uamh Mhor. At our feet Callander nestles beneath its pine-girt crags—the gateway to an enchanted land. Thrice happy is the man to whom the hammer has been the "open sesame" to this wonderful country; for, when weary with the glittering pageant of the mere external beauty of mountain and valley, of stream and lake, of tree and cloud; or if the pen of the great wizard should cease to charm; he has still an inexhaustible supply of truth and beauty, stretching cycle upon cycle backwards toward the dawn of creation itself.

CHAPTER IV

THE METAMORPHIC ROCKS OF THE GRAMPIANS

Rocks of Sedimentary Origin

> And behold, as we look further into it, it is all touched and troubled, like waves by a summer breeze ; rippled far more delicately than seas or lakes are rippled ; *they* only undulate along their surfaces—this rock trembles through its every fibre, like the chords of an Eolian harp, like the stillest air of spring, with the echoes of a child's voice.
>
> Ruskin.

Passing now to a consideration of the materials out of which the Grampian Mountains have been built, we may classify them into three kinds—first, the schists of sedimentary origin ; second, the schists of igneous origin ; and third, the later intrusive rocks. As the bulk of the Grampians is made up of the first of these three classes they will be considered in the above order.

The term 'geosynclinal' has been applied by geologists to a group of sediments which have been accumulated during a long continued period of continental depression ; and this may be considered as the first stage in the building of the Grampians. That the crystalline schists of the Highlands were at one time sediments of the ordinary type, such as sandstones, grits, conglomerates, shales, and limestones, and that they have been accumulated under the ordinary conditions of such deposits, is now placed beyond dispute. Thus we can trace in many of the grits well-rounded pebbles of quartz and felspar, and in some cases fragments of still older clastic rocks, clearly proving their original fragmental character. Current-bedding is often well marked in some of the finer quartzites, while the clastic origin of the shales is shown by their finely banded laminae. In the Upper Arenaceous Zone there occurs a conglomerate made up of boulders of gneiss and granite set in a schistose matrix,—an observation originally made by Macculloch, and certified by James Thomson, a distinguished Glasgow geologist.[1]

As will be seen in the sequel, the clastic structure of these rocks has in many cases become so entirely masked as to make it difficult to decide what the original character of the rock has been. In a typical sedimentary rock the constituents are supposed to be wholly allogenic, whereas in a typical crystalline schist they are wholly authigenic. In the Scottish Highlands nearly every gradation may be found between these two extremes.

The amount of change which these clastic rocks have undergone depends, of course, upon the original nature of the sediments, as well as upon the intensity of the metamorphism. Thus, the finer sediments, such as shales and mudstones, have been comparatively easily cleaved and have had secondary micas set up in them, while the sandstones and grits have offered a more stubborn resistance to the effects of dynamic metamorphism. Over and over again one can see a closely packed and well defined set of divisional planes, passing through a slate or phyllite, but stopping short at a bed of quartzite or grit, which may appear scarcely altered, and with only a few incipient divisional planes here and there. On the other hand, as will be shown later on, the region under notice shows considerable differences in the intensity of the metamorphism which has been superinduced upon it. Thus, while in certain areas it may be comparatively feeble, so that the clastic character of the schists may be quite plain, in other areas, often at no great distance, the metamorphism may have become so much increased as to make it almost impossible to recognize the same group of beds as had been seen elsewhere in the less altered state.

---

[1] Macculloch, *Western Islands*, vol. ii. p. 249, and Thomson, *Trans. Geol. Soc. Glas.* vol. v. p. 210, 1875.

Many interesting features associated with dynamic metamorphism can be observed in these schists. The bedding in the slates may often be seen to be intensely folded, and the folds crossed by cleavage planes, generally parallel to the axes of the folds. In certain areas, such as in the Lower Argillaceous Zone along the frontier Highlands, where, at many points, the metamorphism has been comparatively feeble, the cleavage is of the simpler type, and the only divisional planes to be seen in the rocks are those of bedding, and the system of cleavage planes. In the Upper Argillaceous Zone, or Ben Lawers schists, the cleavage planes have themselves often been intensely folded, and will be found to be crossed by a second set of cleavage planes (see Figs. 26, 27), evidently developed during the folding of the first foliation or cleavage. In some of the more highly crushed and folded areas, not only secondary, but also tertiary, and even quaternary structures may be traced, thus clearly showing that many of the schistose structures which we now see have not been set up by a single movement, but by a series of intermittent movements. Numerous interesting examples of these structures from the highly contorted belt of Cowal have been described by the officers of the Geological Survey in their memoir on that district (see Fig. 13).

Some of the most interesting phenomena in connection with the metamorphism of these schists are to be seen in the beds of grit which constitute our Lower Arenaceous Zone. For instance, strain shadows are well seen in the pebbles of quartz, when a thin section of the grit, viewed in the microscope, is rotated under crossed nicols, so that, instead of becoming totally dark in certain positions, the crystal shows an undulating extinction. Again, the larger pebbles of quartz and felspar often show a distinct parallel elongation along lines of stretching in the schists, and in many cases the pebbles have been cracked across, at right angles to the longer axis, the cracks being occupied by granulitic quartz. In some of the more highly metamorphosed areas, the micas and similar flexible minerals are themselves bent, giving further evidence of the intermittent and consecutive character of the movements in the schists. In the same manner such authigenic minerals as garnet, being susceptible to fracture rather than to folding, have, like the allogenic quartz and felspar, been occasionally elongated along later lines of movement in the fractured schists, and the ruptures filled in by quartz which is itself granulitic (see Figs. 17 and 18).

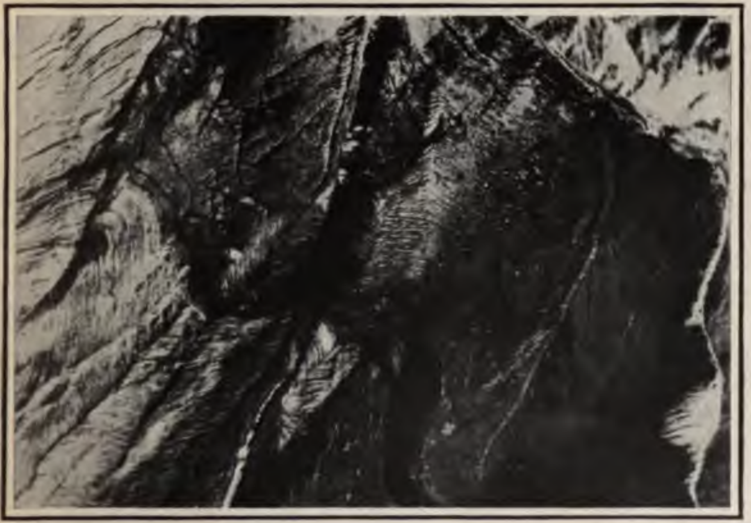


FIG. 13.—Strain-slip in Folded Ben Ledi Grits, Ben Ledi.

Photo. by SAM. FINGLAND.

Without doubt, the Grampians present one of the most interesting areas which we know for the study of such cataclastic structures as have been produced by dynamic metamorphism in the great processes of mountain building. In a typical microscopic section of any of the grits from the Lower Arenaceous Zone, most of the grains of quartz show peripheral deformation, the undeformed centre being generally surrounded by a rim of granular quartz, which has been produced by the breaking up of the original grain. In some instances the clastic constituents of the grit may have been crushed from rim to centre, the whole presenting a finely granular matrix in which remnants of grains, which have escaped deformation, may be detected by their irregular extinction.

A discussion of the manner in which the cleavage and foliation of these rocks has been produced, and of the phenomena connected therewith, would occupy far more space than we can afford, even though such phenomena are intimately connected with the building of the Grampians. It seems to us, however, that both mechanical and chemical causes have been involved in the development of cleavage.

An examination by the microscope of a section of the slates seen along the Highland frontier, will at once explain why they split so readily in the one direction. It will be found that the different constituents of the rock have been arranged in more or less parallel positions (see Fig. 14). If an attempt were made to break the slate or phyllite along the original laminae of bedding, it would be found impossible to do so, or, at least, a very irregular and ragged surface would be the result. This is, of course, owing to the tendency which the slates have to split along the line of least resistance, so that, instead of breaking across a grain of quartz, felspar, or mica, they will split in planes parallel to the longer axes of these particles. A comparison of a piece of slate split along the bedding, with a piece split along the cleavage, will also help to explain the phenomena. In the former case the fractured grains will be quite noticeable, whereas in the latter there will be no such fractured surfaces, as the slate will have split in lines passing between the elongated individual grains (see Fig. 14).

The origin and development of slaty cleavage is a subject which has been long and carefully studied both by geologists and physicists. It was first noticed by Sedgwick, who pointed out its independence of the bedding. In 1846 Sharpe accounted for it by supposing it to be due to the flattening out of the original constituents of the rock. He also believed that, in the Grampians, the foliation planes were arranged in great anticlinals, and that these had been produced when the schists were in a fluid condition—a view opposed to that of Murchison and Geikie, who maintained that they had been produced in clastic rocks at low temperatures by pressure, and that they generally coincided with the bedding, following all the convolutions into which the rocks of the Grampians had been thrown. But we propose to return subsequently to the relationships between the cleavage or foliation planes seen in the schists, and the dynamic forces which have acted upon them.

Sorby, on the other hand, maintained that slaty cleavage was produced by the rotation of the con-

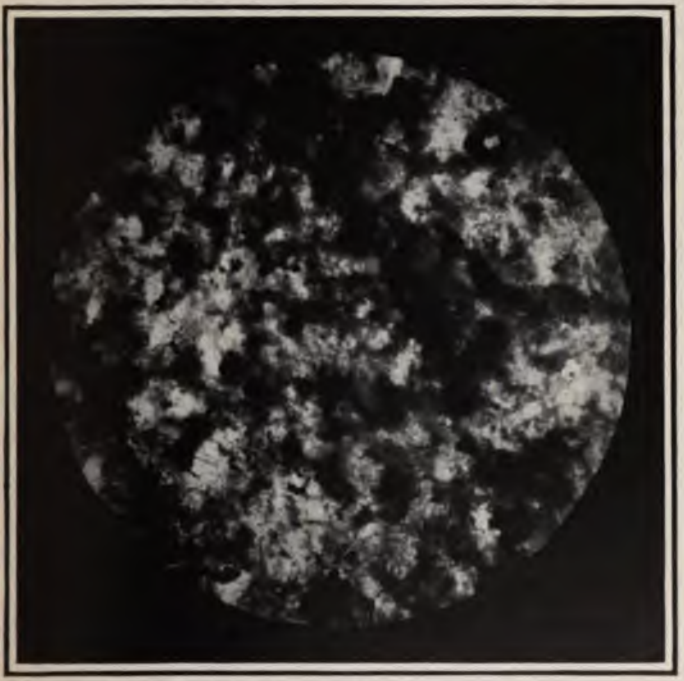


FIG. 14.—Clay Slate, Pass of Leny. (Magnified 40 dias.)

Photo. by JAS. B. CORR.

THE NEW YORK
PUBLIC LIBRARY

stituents of a rock, especially the mica, into such positions as would enable them best to resist further rotation. He backed up this view by an experiment in which he mixed clay and oxide of iron. On subjecting it to pressure he found a series of cleavage planes set up at right angles to the direction of the pressure (see Fig. 16).

Tyndall and Daubrée also experimented with bees-wax, clay, etc., producing perfect cleavage planes in these substances, Tyndall holding with Sharpe that the structure was produced by the flattening of the grains. It will generally be found that the structure known as slaty cleavage has been set up in rocks which have been subjected more or less to lateral pressure; and since this pressure can only on rare occasions, and under particular circumstances, be perpendicular to the bedding, it consequently follows that, generally, the cleavage will be found to cross the bedding at varying angles. As a rule, it will be found that the folding of the rocks and the development of foliation has been contemporaneous in the rocks under discussion. It must, however, be remembered that, besides any such purely mechanical alteration in the structure of the clastic rocks entering into the Grampian geosynclinal, an accompanying recrystallization of the original constituents has also taken place, the most prominent being the production of secondary micas, which generally lie with their longer axes parallel to the lines of cleavage, so that the rock has become more or less crystalline in structure.

Van Hise has recently re-discussed slaty cleavage, and concludes that the structure is due to the arrangement of the mineral particles with their longer diameters, or readiest cleavage, or both, in a common direction; and that the cause of this arrangement is first, and most important, the parallel development of new minerals; second, the flattening and parallel rotation of old and new mineral particles; and third, and of least importance, the rotation into approximately parallel positions of random original particles. He further concludes that this structure is developed in rocks when they are so deeply buried as to be in the zone of plastic flow, and that the structure develops in the planes normal to the greatest pressure.

Besides these more or less structural alterations which have been set up in the clastic rocks by dynamic metamorphism, it will also be found that many of their original constituents have undergone considerable mineralogical alteration. It may be recognized as a fairly general rule that these mineral changes usually take place in the harder rocks before any structural alterations have been effected, whereas in the softer rocks structural alterations usually precede mineral change. As an effect of dynamic metamorphism, alkali felspars may pass into colourless mica, potash felspar producing muscovite, and soda felspar paragonite. Amongst other mineral changes thereby produced we may note the passage of olivine into tremolite and talc.

From what has been said, it will be seen that owing to the clastic rocks which have entered into the composition of the Grampian geosynclinal having been involved in the mountain building process which subsequently upheaved the geosynclinal into a geanticlinal, and having been subjected to high degrees of heat and pressure, the materials of which they were composed have been profoundly altered, both structurally and mineralogically. In this way rocks which were originally of sedimentary and igneous origin have been transformed into slates, schists, gneisses, and other kinds of metamorphic rocks; the movements which have so profoundly altered these rocks being the same as those which upheaved them above the level of the sea in which they were deposited.

It has long been recognized that the different schist zones which enter into the formation of the Grampians traverse that region in a general north-east and south-west direction. A glance at the accompanying map will show the feature at once. Beginning at the Highland frontier, they outcrop in the following order. A narrow band of black shales, cherts, and limestones, the supposed Arenig rocks of the Survey. I. The Lower Argillaceous Zone, consisting principally of slates and phyllites, with subordinate beds of grit and limestone. II. The Lower Arenaceous Zone characterized by the presence of pebbly grits, sometimes passing into conglomerates. Near the top of this zone we have the so-called "green beds," which form a well-marked horizon at this point. III. The Loch Tay Limestone Zone, so called because of its extensive development along the northern and southern shores of Loch Tay. IV. To the north of the Loch Tay Limestone we have the Garnetiferous Schist Zone, characterized by the large quantities of garnets which are found in the schists upon this horizon. V. The Upper Argillaceous Zone, consisting of phyllites, thin beds of schistose quartzites, greywackes, limestones, and dark graphitic shales. VI. The Upper Arenaceous Zone, of which the principal member is the central Highland quartzite, with a band of limesto these schists of clastic origin are associated bands of hornblende-schist, epidiorite, and other such altered basic igneous rocks; a very prominent band of the latter crosses the Grampians from shore to shore, being closely associated with the Loch Tay Limestone. These rocks may be arranged as in the following

TABLE OF THE METAMORPHIC ROCKS OF THE HIGHLANDS.

Moine Schists. Position uncertain.

VI. Upper Arenaceous Zone	Quartzite Grits Boulder Bed	Ben-y-Ghloe, Schichallion, Glen Lyon, Loch Awe, Islay, Jura.
V. Upper Argillaceous Zone	Limestone Black Schist Limestone Phyllites Schistose Quartzites	Glen Shee, Blair Atholl, Ben Lawers, Ben Lui, Loch Fyne, Islay.
IV. Garnetiferous Schist Zone	Mica Schists Quartz Schists	Strath Tay, Glen Lyon, Glen Dochart.
III. Loch Tay Limestone Zone	Limestone Calcareous Schists	Loch Tay, Glen Dochart, Glendaruel, Kilfinan.
II. Lower Arenaceous Zone	Green Beds Grits Conglomerates Greywackes	Ben Vorlich, Ben Ledi, Ben Venue, Ben Lomond, Doune Hill, Loch Eck.
I. Lower Argillaceous Zone	Phyllites Limestones Greywackes Grits	Bridge of Cally, Dunkeld, Loch Lubnaig, Aberfoyle, Luss, Dunoon, Rothesay.
Rocks of Supposed Ordovician Age	Black Shales Cherts Limestones Grits	Cortachy, North Esk, Pass of Leny, Aberfoyle, Kelty Water, N. Glen Sannox.

Schists of Igneous Origin.	Hornblende-schists. Epidiorites. Serpentine. Chlorite-schist.

From the sequel it will be seen that we look upon

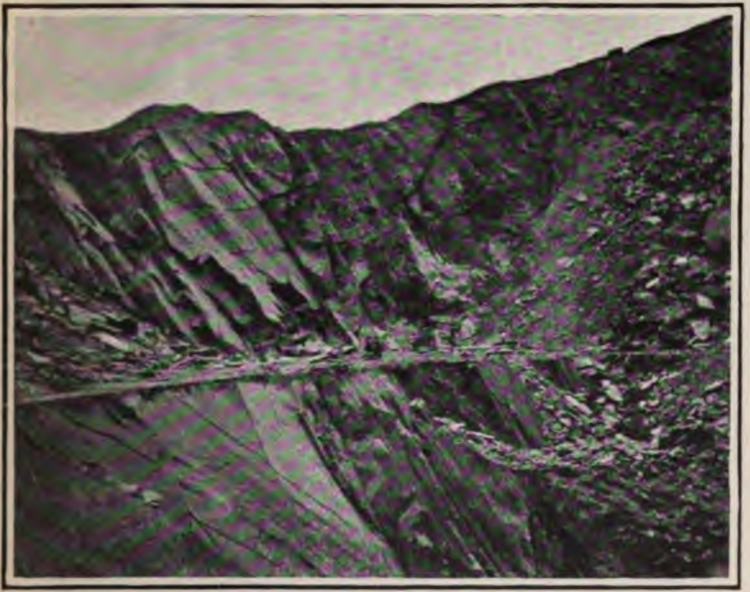


FIG. 15.—Craiglea Quarry, showing Stratification and Cleavage of Clay Slate.

Photo. by H. COATES.

the above table as a descending one, the newest rocks being placed at the top, the oldest at the bottom ; so that, as we traverse the Highlands inwards from the great boundary fault, we gradually rise into newer beds. The exact relationship of the supposed Ordovician Zone seen along the Highland frontier is left as an open question.

Turning now to a more detailed examination of the characters and positions of the different schist zones, we begin with the Lower Argillaceous Zone, seen along the Highland frontier. We omit the problematical Ordovician belt, which will be described later on.

The Lower Argillaceous Zone stretches across the Highland frontier, from the Firth of Clyde on the west to Stonehaven on the east. Between it and the Highland boundary fault there occurs at certain places a group of grits, known as the Leny grits, and here and there the black shales and cherts of the supposed Ordovician belt appear as if wedged in between the boundary fault and the crystalline schists of the interior ; but to the relationships of these two groups we will return again.

In Bute, the Lower Argillaceous Zone is exposed to the north of Rothesay in Kames Bay, between Ardbeg Point and Ardmaleish Point. Crossing the Kyles of Bute, its southern boundary may be traced across the Toward Peninsula, from Ardyne Point, at the mouth of Loch Striven, to a little north of the Bull Rock on the Firth of Clyde, south of Dunoon, while its northern boundary runs from opposite Strone Point to Hunter's Quay. From this point the Lower Argillaceous Zone runs through the Rosneath Peninsula and across the Dumbartonshire Highlands, by Cove, Row, and Luss. Crossing Loch Lomond, it can be seen to the south of Sallochy Wood, from whence it strikes north-eastward by the shores of Loch Ard, being well exposed in the Aberfoyle quarries. The slates have been worked both on the eastern and western shores of Loch Lubnaig at Coireachrombie and at Anie. Pursuing their steady north-east strike, the slates outcrop along the frontier Highlands of Perthshire, passing through the Aberuchill hills, where they have been quarried, by Comrie, Craiglea quarry, north of Logiealmond (see Fig. 15), to Birnam quarries, south of Dunkeld in the valley of the Tay. Thence they can be traced by Forneth, Bridge of Cally, Pearsie, Lethnot, Fettercairn, to Stonehaven on the east coast.

The principal rocks of the Lower Argillaceous Zone are phyllites of various colours, including black, blue, purple, green, grey, and buff, with occasionally intercalated bands of grit, greywacke, and thin limestones. Perhaps the best locality for the examination of this group of beds is the section exposed on the Firth of Clyde between Hunter's Quay and the Bull Rock to the south of Dunoon. Here some excellent tide-washed exposures of the beds forming this zone can be seen. The dip of the principal foliation along the shore of the Firth of Clyde is towards the south-east, at an angle of about 53 degrees. The bedding in the phyllites may be seen to be folded over and over again, but the foliation generally keeps straight across the original lines of bedding, and is parallel to the axes of the folds affecting the bedding, from which it may be inferred that the finer argillaceous materials have suffered considerably more folding than the massive arenaceous beds. The bedding in the phyllites can generally be detected by differences in their shading or colouring; also differences in the texture help to point out the original lines of stratification, some of the bands being more gritty than others (see Figs. 15 and 16).

In the East Bay at Dunoon there is an interesting section which shows that the lines of foliation have been themselves folded by subsequent movements. In his description of this section, in the Geological Survey Memoir of Cowal, Mr. Clough points out that the direction of the hade of these folds is not always the same. Sometimes they may be seen to hade north-west, at other times, south-east, the latter examples seeming to be the most prominent. As a rule, in the Southern Highlands the over-folding has generally been south-east, and this occasional reversal of the law may be accounted for by the supposition that the schists along the Firth of Clyde have been pushed over towards the north-west. In this section there are numerous crystals of iron pyrites, largely altered into limonite, the cores being still iron pyrites. Sometimes these are half an inch in length. Round each crystal is an oval zone in which the phyllites have been bleached into a pale cream colour, probably from a reduction of the iron. It would thus seem that the pyrites crystals had been developed subsequently to the last movement in the rocks, as they show no evidence of deformation. Eyes of pyrites, similar to those described by Mr. Harker in the *Geological Magazine* for 1899, may be seen in the slates at Undraynian Point to the north of Kames Bay. The pyrites in this case seems to have been of early origin and to have been flattened out, parallel to the cleavage planes, leaving vacant spaces, which were subsequently infilled with crystalline quartz. Along the shore, between Hunter's Quay and the Bull Rock, numerous exposures will be found of thin beds of schistose limestone. They are well exposed north of Kirn pier, and also a little to the north of Dunoon pier. They are never more than a few feet thick, and appear to be intercalated between the bedding planes of the phyllites. They weather to a rusty grey colour, but fresh fractures show a dark grey colour. Sometimes also they are pure white, like statuary marble. It will be noticed that these thin limestones have generally suffered as much, if not more, folding than the neighbouring phyllites—a similar feature to that seen in the more massive limestones of Loch Tay.

Along the Dunoon shore, and south of Glen Morag, a continuous exposure will be found of buff, grey, and purple phyllites, in which the principal foliation is seen to dip south-east. In places, the principal foliation is crossed by a later one, which cuts the earlier foliation almost at right angles and shifts it at these points to the south-east by slight throws. An interesting exposure of limestone, which has been rendered schistose and the planes of foliation folded by subsequent movement, and crossed by *Ausweichung* or strain slip, may also be examined here. A close examination will show that there has existed an earlier strain slip which has itself been folded, so that the limestones seem to have been particularly liable to folding and refolding. At this point of the section some fine examples showing the relationships of the stratification in the phyllites to the foliation

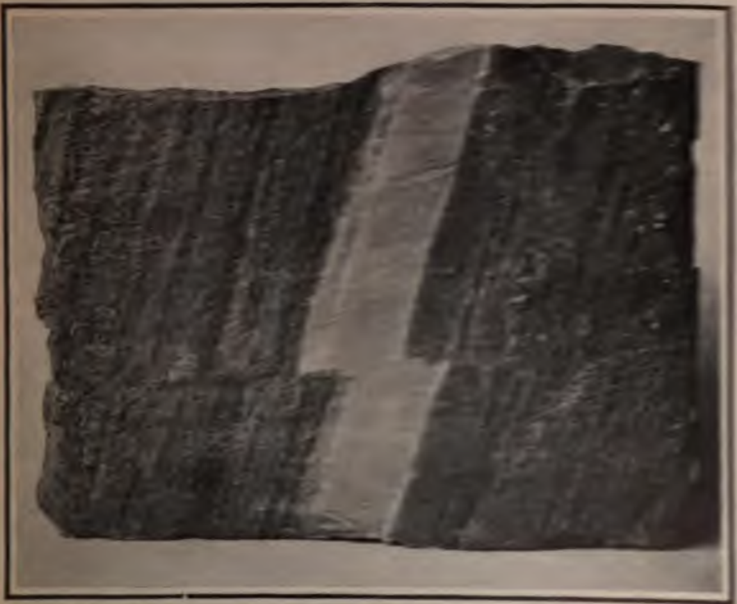


FIG. 16.—Cleavage, Stratification, and Reversed Fault, in Clay Slate.

Photo. by WM. ELLISON.

may also be observed. Mr. Clough, in the Survey Memoir on Cowal, has noticed that it is generally the upper limbs of the folds in the bedding that are most thinned, which is contrary to the general law, namely, that the under limb ought to be the most thinned. Mr. Clough explains this by the supposition that in the ridging up of the great anticlinal axis, which, according to the Survey, passes through Cowal, these folds in the bedding received a position not originally their own; but in fact they have become inverted. While recognizing this most interesting observation of Mr. Clough's, we think that the occurrence may be accounted for in a somewhat different manner, by supposing that the beds along the Firth of Clyde have been bent over and pushed inwards towards the north-west. In other words, while the early overfolding of the bedding has generally faced the south-east, this has been inverted along the Firth of Clyde by the development of another fan-structure of which we only see the northern limb. But this will be treated further on in greater detail. At Luss, the slates appear, according to the recently published map (sheet 46) of the Geological Survey, to be broken up into four distinct outcrops by infolds of the Leny grit, which appears to occupy a horizon lower than the slates. At Loch Lubnaig, the Lower Argillaceous Zone is well seen on the hill sides which form its eastern boundary, where the rocks consist of green and purple slates. Both the bedding and cleavage dip N.N.W., the latter at 70°. The cleavage can be seen crossing the bedding at angles varying from 20° to 60°, thus showing that the beds have been through Ben Ledi and Ben Vorlich, by St. Fillans and Ben Chonzie, down Strath Bran and eastwards across the frontier Highlands of Forfarshire and Kincardineshire.

The massive grits of this zone, known by the Survey as the Ben Ledi grits, appear to come on immediately above the slates and phyllites of the Lower Arenaceous Zone. The rocks of this zone vary from exceedingly fine-grained greywackes to massive grits with pebbles often an inch in diameter. The pebbles are usually quartz and felspar set in a finely comminuted felspathic matrix (see Figs. 17 and 18). On Stuc a' Chroin the grits become very coarse, in fact they might almost be called conglomerates, the pebbles being mostly quartz. As has already been pointed out, to the west of Loch Katrine these grits have suffered a considerably higher dynamic metamorphism than further to the east, where they are only slightly sheared and still preserve their original clastic character. To the west of Loch Lomond these massive grits have in many places become so completely deformed as to present all the features of a typical gneiss. Still, here and there, in areas of more feeble metamorphism, relics of the original clastic grains can be traced, thus placing beyond doubt their sedimentary origin.

When highly altered, these rocks might be fitly described as granulitic biotite-gneisses, as scarcely any allogenic material can be recognized in their constituents. The quartz is generally the most abundant, the felspar being less so. The original quartz and felspar have become completely granulitized, and now exist as a fine mosaic of interlocking grains. The mica

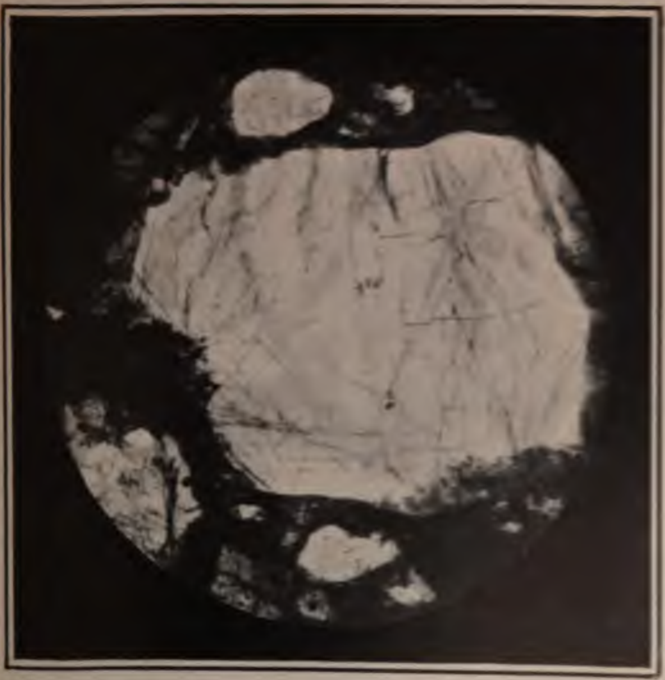


FIG. 17.—Ben Ledi Grit, Ben Ledi. (Magnified 40 dias.)

Photo. by JAS. B. CORE.

PUBLIC Library
ASTOR, LENOX AND
TILDEN FOUNDATIONS

is arranged in flakes along the planes of schistosity in the rock. Mr. Teall says of such a rock that all the constituents are authimorphic, and most, if not all, are authigenic.

Mr. Teall, in summing up the characters of these rocks, says that they "consist of foliated crystalline rocks, essentially composed of quartz, felspar, and one or two micas. They are therefore gneisses in the usual sense in which that term is employed. Where conspicuous traces of their clastic origin remain they may be termed gneissose grits; when all, or nearly all, such traces have disappeared, they may be termed granulitic gneisses. They pass by insensible gradations into felspathic mica-schists."

Above these grits occurs a set of rocks known as the "green beds," because of their marked greenish colour. They generally show a more or less well-developed schistose structure, and are characterized by the presence of granular epidote, chlorite, and dark green or brown biotite (see Fig. 19). That they are of fragmental origin seems undoubted, but their original character seems uncertain. When first mapped by the officers of the Survey they were supposed to be of pyroclastic origin, the green colouring matter being looked upon as similar to the fine dust of volcanic tuff, but the complete absence of interbedded lava-flows, or of any pebbles referable to igneous rocks, throws doubt upon such an origin.

The "green beds," like the schists already described, have been traced across the southern Grampians for a considerable distance. In Cowal they stretch from Ardmarnock Bay, by Glendaruel, to the head of Loch Fyne, and from thence eastward towards Glen Falloch.

This may be considered as the main line of outcrop. Outliers have been traced on Sron Aonaich, a shoulder of Ben Lomond, in the railway cutting at the head of Loch Lomond near Ardlui, on the shores of Loch Chon, on the northern slopes of Ben Venue and the eastern end of Loch Katrine, and on the summit of Ben A'an.

Stratigraphically, the "green beds" occupy a position near the top of the Lower Arenaceous Zone (see Figs. 51 and 52), and occur on a horizon not far below the Loch Tay Limestone. It was not until considerable advance had been made in the mapping of the Highlands that the Survey were enabled to recognize the importance of the "green beds" as a definite and well marked horizon amongst the schists to the south of the Loch Tay Limestone. Towards the great central *Fächer*, or fan structure, the "green beds" dip in simple outcrops below the Loch Tay Limestone. Between that great axial line of folding and the frontier Highlands they are repeated again and again, in isoclinally folded strata, as outliers between the folds of the Ben Ledi grits. In Cowal there appear to be two sets of the "green beds."

The following is a description of the "green beds" from two localities, as seen in thin sections under the microscope. The first is taken from Sron Aonaich, a shoulder of Ben Lomond, and the second from a cutting in the West Highland Railway north of Ardlui, at the foot of Stob an Fhithich. On comparing the two specimens, it will be seen that the specimen from the latter locality exhibits an increasing metamorphism. The green beds of Sron Aonaich consist principally of pale yellowish green grits, in

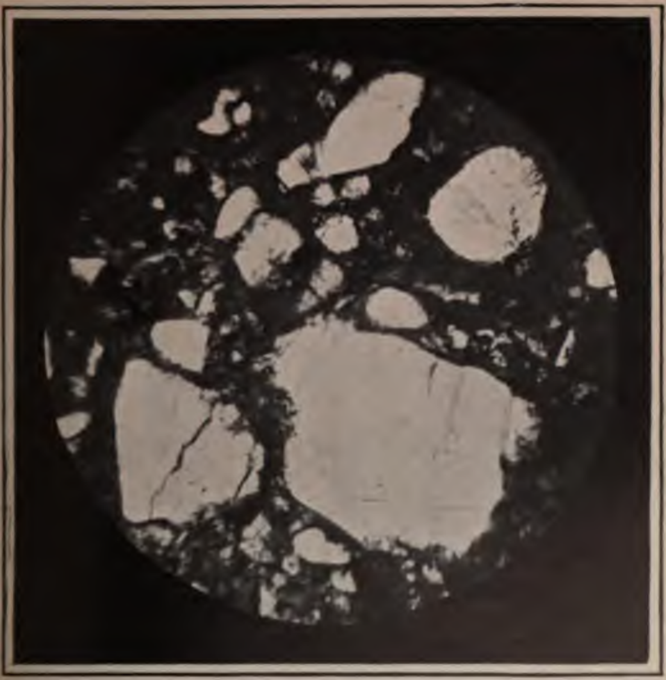


FIG. 18.—Ben Ledi Grit, Ben Ledi. (Magnified 25 dias. Crossed Nicols.)

Photo. by JAS. B. CORR.

which the original clastic structure is evident, as they are often seen to enclose large pebbles of quartz and felspar. Examined in a thin slice under the microscope the rock is seen to be composed of epidote, quartz, felspar, chlorite, biotite, and two sets of long needle-shaped crystals, one of which gives straight extinction and has a positive sign, while the other has an extinction angle of about 14° and may be hornblende. The epidote is in small rounded grains, which sometimes appear to be aggregated together; it is of a greenish yellow colour, and gives the general colour to the rock. The larger grains show a slight pleochroism. The epidote, which appears to form the bulk of the rock, can be distinguished from the other constituents of the rock by its high refractive index and strong double refraction. Inclusions of epidote occur in some of the larger felspar grains. Chlorite exists in considerable abundance in the form of flakes, and is of a light green colour. Usually the pleochroism is not very strong, but in some cases it gives well marked green and brown tints. The larger pebbles of quartz and felspar are usually surrounded by a mosaic of granular material, the felspars often showing turbid centres. In several instances the twinning bars of the felspars can be detected in the undeformed portions of the grains. In other cases the pebbles have been crushed from rim to centre, the existence of the sand grain being indicated by the aggregations of granules of quartz or felspar. Under crossed nicols a system of strain shadows may be seen in several of the uncrushed felspars and quartz grains. Biotite occurs abundantly in most of the "green beds," with a distinct cleavage and strong pleochroism in reddish, brown, and yellow tints. The quartz, like the felspar, has generally become more or less broken down, and now appears aggregated together in lenticular-shaped areas. Around these lenticular areas the flakes of biotite and chlorite are arranged, giving the rock a more or less well-developed *Augen* structure. Immediately to the north of Ardlui station there is a considerable cutting in the railway, and the rocks of the cutting have been identified by the Survey as belonging to the "green beds." They will at once strike the observer as being in a much higher state of metamorphism than those already described, as they now exist as dark hornblende-schists, which would at once be considered to be an altered basic rock. According to the Survey, however, many of the hornblende-schists which appear near the great axial line of folding, and which are evidently upon the same horizon as the "green beds," are simply the same beds in a more advanced state of metamorphism. A number of more gritty bands appear intercalated with the hornblende-schists, and these have now become quartz-epidote-schists with hornblende and felspar, or an albite-gneiss with chlorite and hornblende (see Fig. 19).

It would be difficult to speak definitely as to the original character of the "green beds" and the conditions under which they were deposited. They are clearly of clastic origin, though they have now, in many cases, become almost wholly crystalline. The broken and shattered grains of quartz and felspar may form part of the original sediment. The other minerals we should feel inclined to look upon as of secondary origin.

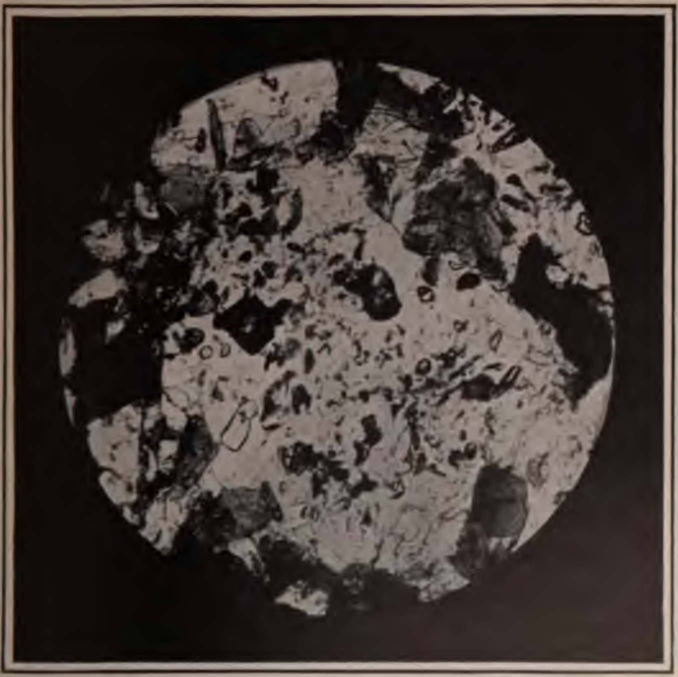


FIG. 19.—Epidote-Schist (Green Beds), Loch Katrine. (Magnified 40 dias.)

Photo. by JAS. B. CORR.

To the north-west, and apparently above the Lower Arenaceous Zone, we have one of the best marked horizons amongst the schists of the southern Grampians—that known as the Loch Tay Limestone Zone. It forms a well marked datum line, separating the lower from the upper schist zones. This zone, like those already described, can be traced right across the whole breadth of the Grampians from sea to sea. It is named the Loch Tay Limestone because of its great development in the neighbourhood of that loch. The Loch Tay limestone has been traced from Kintyre across Loch Fyne to Auchalick Bay, whence it passes across Cowal by Acharossan, Kilfinan, and Glendaruel to Ballimore, south of Strachur. Striking eastward, it can be traced into the valley of the Dochart, outcropping along the hills to the north from near Crianlarich to Auchlyne, where it is cut off by one of the powerful north and south faults. (See sketch maps of Loch Tay District.

In the neighbourhood of Killin and Loch Tay a large number of interesting sections of the Loch Tay Limestone are exposed. It can be well seen in the bed of the Dochart, about a mile above the falls. Here the bed of the river is somewhat rocky, the river flowing over an exposure of the limestone, dipping towards the north-west beneath Sron Clachan. From the bed of the river the limestone appears to ascend the side of Sron Clachan to near the escarpment known as Cnoc a' Mhanaich. Traced eastwards round Sron Clachan, the limestone evidently covers the whole of the ground between the main street of the village and the 1000 feet contour line. It may also be seen at various points, as above the manse and at Maragowan. From this point the limestone stretches along the side of Loch Tay, forming the base of Creag na Caillich and evidently dipping at a considerable angle below that mountain. Numerous fine sections may be observed along the road which leads to Kenmore. For instance, there is an example on the road about half-a-mile beyond the inn and immediately on this side of the keeper's house, probably the Druim na Lairig of the inch Ordnance Survey map. At this point the main body of the limestone is seen to dip towards the north-west at an angle of about 45°, and an examination of it shows that it is banded with thin laminae of argillaceous material which has passed into mica. The limestone has been thrown into a number of folds, which are very clearly shown owing to the banded structure. The longer axes of the folds are seen to hade distinctly with the main body of the limestone, that is, towards the north-west. The over-folding is consequently towards the south-east, while the under limbs of the folds are those which are most thinned. From this it would appear that the direction from which the thrust has been applied was the north-west, and it has been transmitted towards the south-east. We find that, as a rule, this seems to have been the general law of folding observed in this part of the Highlands (see Figs. 46 and 47).

Along the southern side of Loch Tay the limestone is well exposed in the bed of the stream, which, flowing from Lochan Lairig Eala near the head of Glen Ogle, joins the river Dochart at Easter Lix. Ascending the stream a somewhat extensive outcrop of the limestone is passed over. It apparently dips towards the north-west, but gets gradually flatter as we ascend the stream.

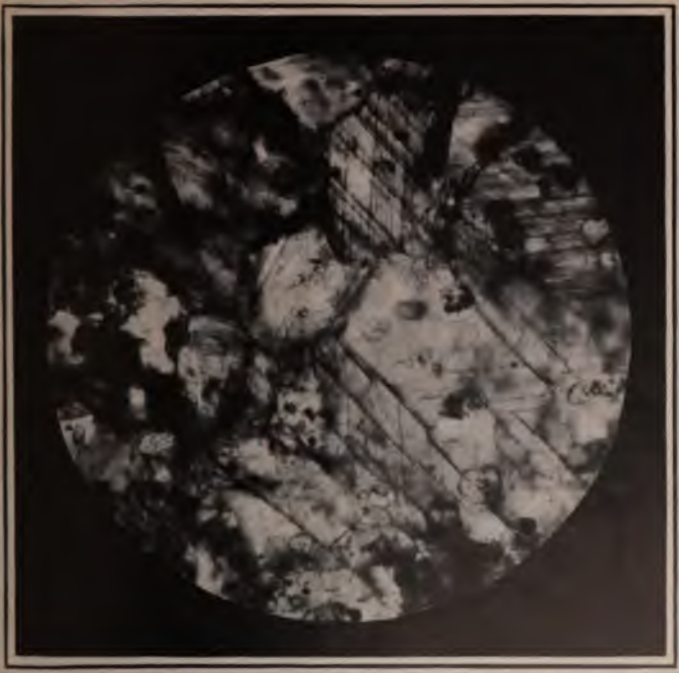


FIG. 20.—Limestone, Loch Tay. (Magnified 25 dias.)

Photo. by JAS. B. CORR.

A similar section is seen in the Ardchyle Burn, between the village and the ford. Near the village the dip is distinctly north-west, but, in ascending the burn, the dip becomes gradually flatter and flatter, till it eventually rolls over and appears to dip south-east and under Creag Mac Ranaich. At Glen Ogle head an exposure of the limestone is seen by the roadway near the station. Here the limestone has been considerably folded and appears to dip towards the south-east (Fig. 47). From the head of Glen Ogle the limestone can be traced more or less continuously along the northern side of Ben Leathan; and, though it is much covered with drift, excellent sections of it may be seen in the beds of the Allt nan Sliabh and the Allt an t-Socaich, at a point a little higher up the hill-side than where they unite. From this the limestone can be traced along the hillside to the north of Creag Gharbh, where it is thrown out by the powerful fault which runs across Loch Tay to the east of Ardeonaig. On descending Glen Ogle, the limestone, which was seen at its head, disappears for the space of about two miles, but again appears, accompanied by beds of epidiorite, about half-way down the glen in the bed of the stream. The dip of the schists is now almost flat, or slightly to the north-west. From the foot of Glen Ogle the limestone may be followed in a large horse-shoe curve up Gleann Ceann Droma. Bending round the foot of Meall an t-Seallaidh, its outcrop sweeps round the Kirkton Glen and back into the main valley of the Dochart. At the head of Loch Earn the limestones seem to undulate gently towards the south-east, plunging below the garnetiferous schists of Meall nan Uamh to the east of Balquhidder

Station, and abutting on the Glen Ample fault, which is a continuation of that already noticed as crossing Loch Tay. From the northern shores of Loch Earn, near Dalveich, the limestone may be traced up Glen Beich on the west side of this fault for nearly three miles. Outliers of the Loch Tay Limestone also appear on the summit of Ben Vane to the north of Ben Ledi and on Meall na Creige above Ardeonaig.

From the Loch Tay district, where this limestone zone is so well developed, and where its relationship to the other schists is comparatively clear, it can be traced eastwards down the valley of the Tay.

The Loch Tay Limestone varies in colour, from white, through different shades of grey, to nearly black. It is in a thoroughly crystalline condition, and the grains of calcite vary considerably in size. In some cases the rock is fine-grained, and the calcite crystals are microscopic, while, in others, they may be half-an-inch across. At times it appears as if the black crystals were set in a matrix of smaller crystals of a greyish or white colour. Mr. Clough has suggested that this colour may be accounted for on the supposition that the white parts have been formed by a crushing and recrystallization of the darker parts (see Fig. 20).

The presence of small flakes of pale-coloured mica in the limestone is not uncommon, the quantity increasing at times to such an extent as to make the limestone pass into a calcareous mica-schist. In many cases the rock presents a distinctly banded appearance owing to the alternation of micaceous and calcareous laminae. Whether this may represent an original structure in the rock, or whether it has been brought

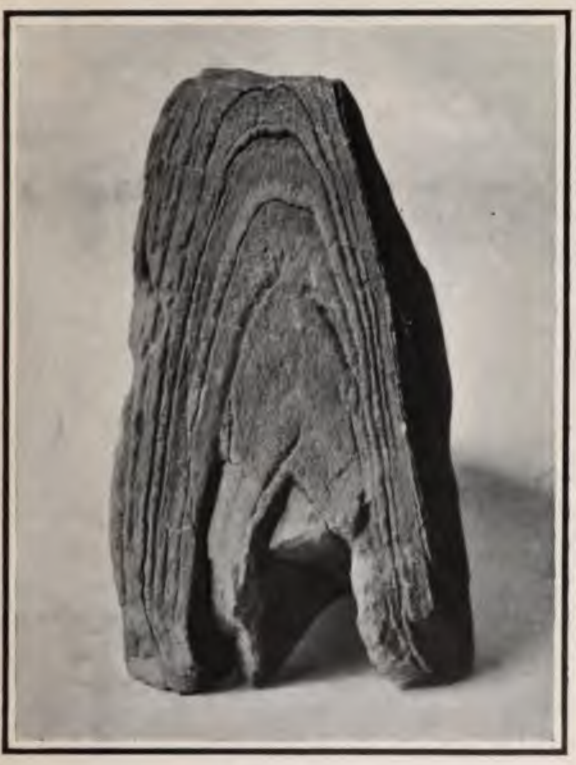


FIG. 21.—Folded Limestone, Glenample, Lochearnhead.

Photo. by WM. ELLISON.

about by subsequent deformation, is not quite clear. Probably it may be due to both causes.

Mr. Teall has identified certain pale straw-coloured or white needles, which appear on the weathered surface of some of the impure limestone bands, as idocrase. Garnets also occur at certain places in the impure calcareous schists.

Mr. Clough has estimated the thickness of the Loch Tay Limestone in Cowal to be from 40 to 50 feet, it being divided by a bed of hornblende-schist. In the district of Loch Tay it cannot, we think, be very much thicker, though it presents outcrops varying from half a mile to nearly a mile in extent, and that on steep hill sides and with a dip of 45°. This great thickness of the outcrop can only be accounted for on the supposition that the limestone has undergone considerable folding, and, though we have not yet received any very reliable data as to the extent of this, yet the whole aspect of the limestone points most conclusively to the fact that considerable folding must have taken place.

It is almost impossible to examine the Loch Tay Limestone at any place without being struck with the remarkable manner in which it has been folded. Evidence of this is, of course, best seen where the banded structures, to which we have just referred, occur. Not only has it been plicated into comparatively deep isoclinal folds, but the limbs of these larger folds have themselves often suffered folding, so that the limb of a larger fold may be plicated into innumerable smaller ones, whose limbs all hade in the same direction. Interesting examples of these phenomena have already been referred to as occurring at Druim na Lairig near Killin, and at the Glen Ample falls near Lochearnhead, but they abound everywhere and can generally be seen where the limestone outcrops (see Fig. 21 and Fig. 46).

To the north-west, and apparently above the Loch Tay Limestone, we have the Garnetiferous Schist Zone, so called because of the great quantities of garnets which appear in the schists. It is not asserted that these garnetiferous schists mark a definite stratigraphical horizon, yet it is somewhat remarkable that they can be traced right across the Grampians in a manner similar to the schist zones already described. Their southern boundary has been drawn at the top of the Loch Tay Limestone, and their northern at the base of the Upper Argillaceous Zone. They appear on the shores of Loch Fyne at Kilfinan, and strike north-eastwards, bounded on the north by the Ardrishaig phyllites and on the south by the Loch Tay Limestone. Passing from Cowal into Perthshire, the garnetiferous schists can be traced from Tyndrum, eastwards by Glen Lyon and Glen Dochart, to the foot of Loch Tay, whence they stretch by Aberfeldy and Pitlochry into Forfarshire and Banffshire. As we have already said, we would not care to affirm that the garnets actually mark a definite stratigraphical horizon, but that they exist in great numbers in a group of schists, which evidently lie between the Ardrishaig phyllites on the north and the Loch Tay Limestone on the south, seems to be quite conclusively established. It may also be remarked that the garnets are not confined to the sedimentary schists alone, but are developed also in the epidiorites and hornblende-schists, which occur upon this horizon. It

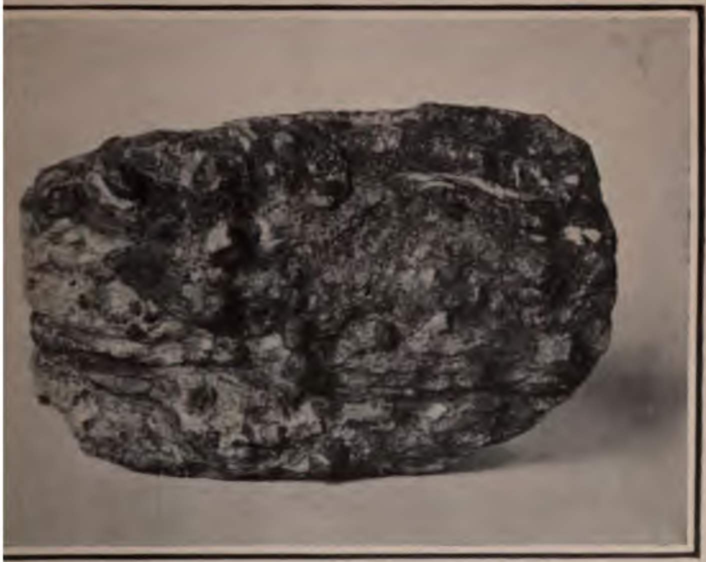


FIG. 22.—Garnetiferous Mica-Schist, Aberfeldy.

Photo. by WM. ELLISON.

is also noticeable that they appear to increase in size and number from the south-east towards the north-west (see Fig. 22). It seems, then, that the garnets are the product of dynamic metamorphism. That gradually increasing metamorphism has taken place from the frontier Highlands inwards, towards the great axial line of folding or backbone of the Grampians, is, we think, a matter now placed beyond dispute. We would also naturally look for an increasing metamorphism towards the core of the great geanticlinal, where the beds could not be jammed any closer, and where arrested motion would generate heat. It will also be seen that, proceeding inwards from the Highland frontier, it becomes more and more difficult to trace the original clastic structures in the sedimentary schists as we approach the great axial line of folding.

Mica-schist may be taken as the typical rock occurring within this zone. Mineralogically, mica-schist consists of an aggregation of quartz and mica arranged in alternating wavy laminae-planes of schistosity. Structurally, the quartz presents a granular character, having been derived from the breaking up of the original quartz grains in the clastic rock. The mica, which may either be muscovite or biotite, is entirely authigenic, and takes the form of plates, which are generally basal sections of the mineral. They are often arranged in continuous layers, along which the rock splits more readily, and which present surfaces covered with glistening mica (see Fig. 23). An infinite number of varieties may occur, according to the predominance of one or other of the constituent minerals, so that a typical mica-schist may pass, on the one hand, into a phyllite, or, on the other, into a quartz-schist. Various accessory minerals may occur in the schists, as felspar, kyanite, staurolite, chlorite, or garnet.

The common accessory mineral in the mica-schist is, of course, garnet, the crystals of which are of a port wine colour, and vary in size from minute crystals which can only be seen under the microscope, up to those which may be half an inch in diameter. In many cases the garnets are surrounded by a rim of chlorite, and show evidence of having been stretched in the direction of the foliation planes. They are also seen to be cracked across at right angles to their longer axes, and the cracks filled in with granulitic quartz. These phenomena point to the fact that a certain amount of movement must have taken place in the schists at a period subsequent to the crystallization of the garnets (see Fig. 23).

Above the Garnetiferous Schist Zone we have the Upper Argillaceous Zone, which consists of rocks of a more argillaceous type than those just described. They are represented by phyllites or calcareous sericite schists, and dark graphitic schists and limestones. With the former are associated thin beds of greywacke, or fine-grained schistose quartzite (see Figs. 26, 27 and 28). This zone can be traced from Loch Killisport across Knapdale to Ardrishaig, and thence along both the eastern and western shores of Loch Fyne, passing Inveraray and Ben Bhuidhe, and sweeping round Ben Laoigh into Perthshire. From Tyndrum a band of considerable width stretches north-eastwards towards Glen Lyon, forming the main outcrop in this area. Another band of considerable width stretches from Meall Chuirn, on the ridge between Glen Lochay and Glen Dochart, eastwards by Creag na Caillich, Meall nan Tarmachan, Ben Lawers, Fernan, the ridge between

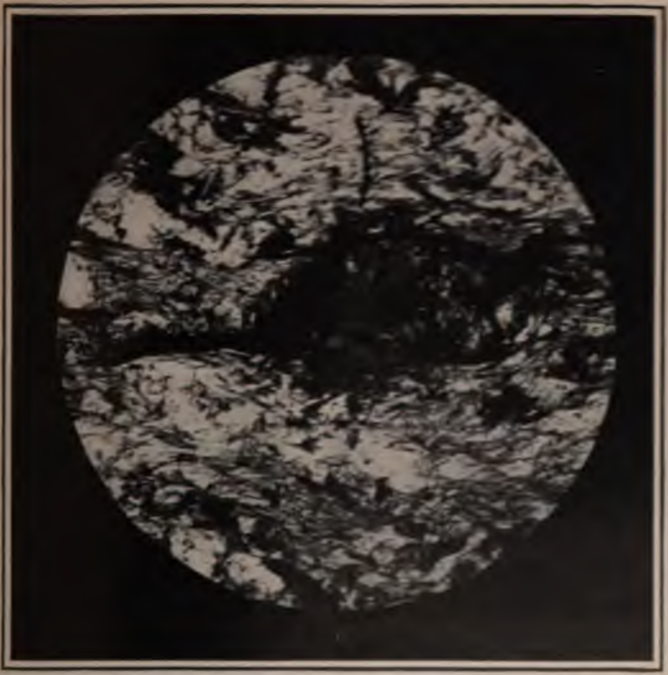


FIG. 23.—Garnetiferous Mica-Schist, Killin. (Magnified 40 dias. Crossed Nicols.)

Photo. by JAS. B. CORR

the Tay and Tummel, to Ben Vrackie, above Pitlochry, and thence north-eastwards into Kincardineshire and Banffshire.

The phyllites of this zone are highly micaceous rocks, the sericitic mica occurring in flakes lying parallel to the general schistosity of the rock. Granular quartz also occurs in lenticular masses, round which the mica flows in wavy laminae. They usually contain numerous veins of extravasated quartz, which have been folded along with the schists. In central Perthshire these schists have become thoroughly crystalline in character, so that all traces of their original clastic structures have been destroyed. Mr. J. B. Hill in a paper on "The Progressive Metamorphism of some Dalradian Sediments in the Region of Loch Awe," has shown that these phyllites in the neighbourhood of the Pass of Brander exist in the condition of clay slates, which, though they are cleaved, still exhibit their bedding planes quite distinctly. Traced eastwards beyond Dalmally, these slates are seen gradually to pass into mica-schists, assuming a highly crystalline character, containing big flakes of white and green mica and chlorite (see Figs. 24 and 25).

Apparently intercalated with these phyllites are thin beds of fine-grained greywackes and quartzites, the former being of a dark grey colour, and often finely banded, the latter being usually pure white. It was in these beds that the late Duke of Argyll and the author discovered certain bodies, which they considered to be of organic origin, and which they supposed represent deformed annelid tubes. The specimens found by the author occur in dark greywackes near the summit of Creag na Caillich. On weathered surfaces they either stand up in little knobs or present a series of pits, according as they are harder or softer than the surrounding matrix. In sections at right angles to the bedding, they usually present an oval form, or they may be drawn out into lenticular streaks, when the shearing has been more intense. They also occur on the bedding planes in ribbon-like forms, the materials within the tube being of lighter colour than the matrix. The bodies discovered by the late Duke of Argyll generally occur in the thin bedded quartzites, which are intercalated with the phyllites, and are well exposed along both the eastern and western shores of Loch Fyne. They present features similar in every respect to those just described from Creag na Caillich, and he believed them to be undoubtedly of annelid origin. Another member of the Upper Argillaceous Zone, which forms a very definite horizon in the Highland schists, is a black graphitic schist, which appears to come on immediately above the Ardrishaig and Ben Lawers phyllites. The outcrop of this schist can be traced from Dalmally to Tyndrum, whence it strikes north-eastwards from the Crom Allt, by Beinn Chaorach, Cam Chreag, Meall Tionail and Meall a' Chall, this being the main outcrop, and along which it is seen to plunge below the quartzites of the Upper Arenaceous Zone. Outliers of the black graphitic schist have been infolded with the Ben Lawers phyllites on Meall Corranaich, a mountain a little to the north-west of Ben Lawers, and they extend eastwards toward Fernan.

The recent work of the Geological Survey in the Pass of Killiecrankie and the neighbourhood has confirmed the relationships which we have long believed

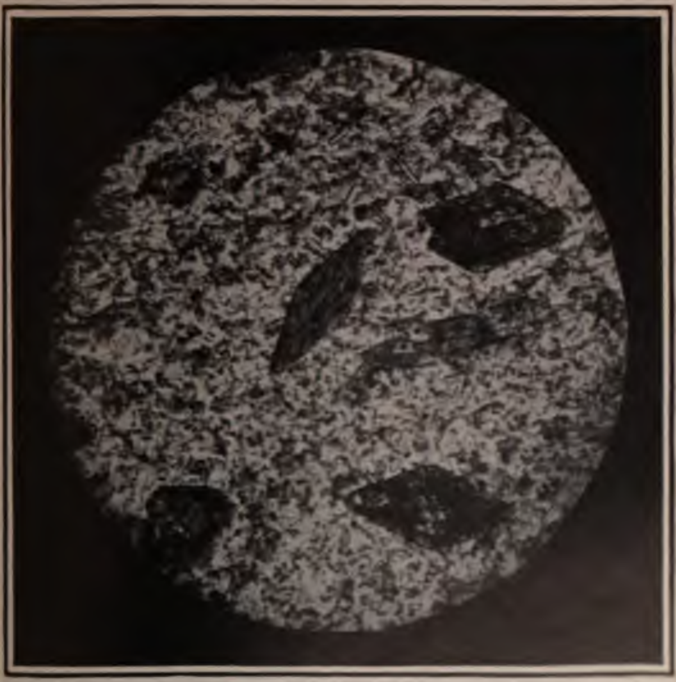


FIG. 24.—Greywacke, with Hornblende, Creag na Caillich.
(Magnified 40 dias.)

Photo. by JAS. B. CORR.

to exist between the phyllites, black schists, and quartzites, of the Ben Lawers Massive.

The evidence regarding the succession of the phyllites, black schists, and quartzites upon this horizon has been arranged under three heads by Mr. Craig: (*a*) structural evidence, (*b*) petrological evidence, (*c*) evidence from observation of pitch, and discordant junction of different members of the series. We only quote the structural evidence, which shows that in the Pass of Killiecrankie the order of succession is much the same as that seen on Ben Lawers and in Glen Lyon, namely, that the main outcrop of the black schist, which to the north plunges beneath the quartzites, is repeated to the south by outliers infolded in the Ben Lawers phyllite.

We quote Mr. Craig's description of the black schist seen on Meall Uaine in the Pass of Killiecrankie (see Fig. 54). "The first point of importance," he says, "is the identification of the dark schist south of the main quartzite outcrop with that north of the outcrop. On Meall Uaine the so-called graphite schist can be traced round the folds of the base of the quartzite into the black schist to the northward associated with the Blair Atholl Limestone. There is no drift obscuring the ground, and the section is remarkably clear. The basal edge of the quartzite is seen folded with the underlying schist, and usually much drawn out by shearing at the actual margin, but a few inches farther in the quartzite is fairly solid.

"Minor zones in the black schist can also be identified on both sides of the outcrop of the quartzite. The thin dark limestone already alluded to is seen in several localities south of the quartzite outcrop. Near the summit of Meall Uaine it is found more highly altered and beginning to develop tremolite crystals. North of the quartzite it has the same appearance, but as we proceed north-eastward into a region of greater metamorphism the tremolite becomes more conspicuous and more highly crystalline, till the rock presents the appearance of the well-known Tremolite Limestone, which has so often been recorded as a zone in the black schist associated with the Blair Atholl Limestone.

"This identification of the black schist with the so-called graphite schist is further confirmed by the mapping of the Ben Lawers schist, with its characteristic thin limestone band, round from south to north of the outcrop of the quartzite.

"This evidence is sufficient to establish the fact that the quartzite is the highest member of the series. It lies above the black schist, and when it comes in contact with the Blair Atholl limestone, as near the head of Allt a' Mhagain, it must be above that deposit also."

We have quoted Mr. Craig's conclusion at some length, as we think he has established the identity of the black schist to the north with the graphite schist overlying the Ben Lawers phyllites, and thus brought this region into line with that farther to the west. He also seems to have no doubt as to the order of succession, which is identical with what we have maintained for a number of years, and is essentially the same as that advanced by Nicol some forty years ago. So remarkable is the confirmation of Nicol's succession that we do not hesitate to quote him also. Speaking of the lower parts of Glen Shee, he says: "The greater part of this glen lies in the mica slate, the beds showing a general inclination to the north, though much con-

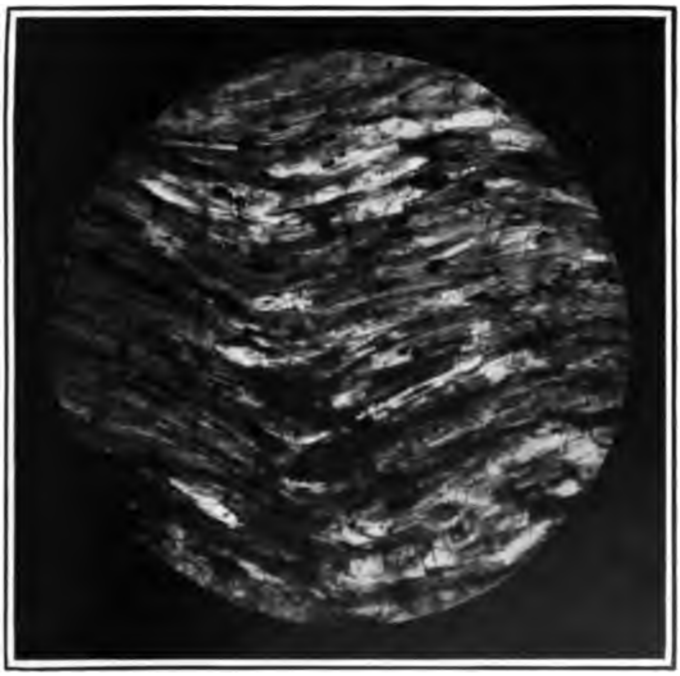


FIG. 25. —Ben Lawers Phyllite, Creag na Caillich.
(Magnified 40 dias.)

Photo. by JAS. B. CORR.

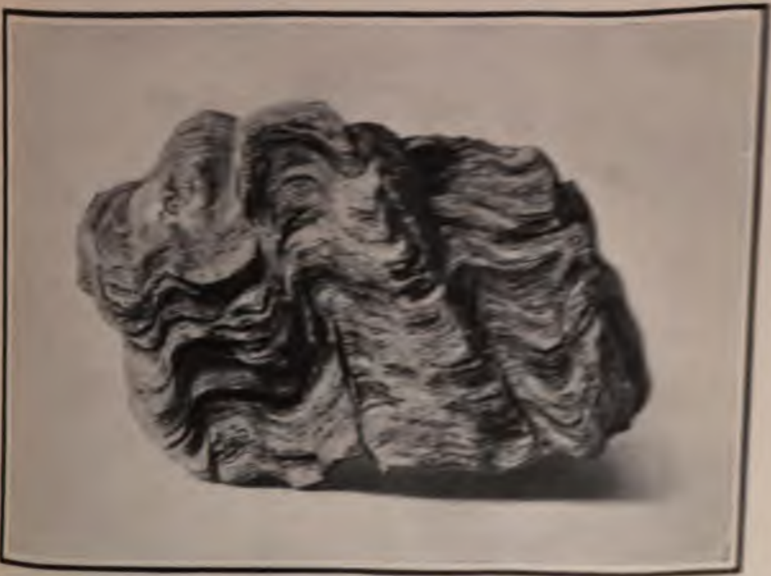


FIG. 26.—Ben Lawers Phyllite, showing strain slip, Ben Lawers.

Photo. by WM. ELLISON.

cealed in the lower valleys by detritus and occasional convolutions. North of the inn, at the Spital, I found a black carbonaceous shale in highly contorted beds, but dipping 60 degrees to N. 12 degrees W. This rock closely resembles the black shales of Oban and Easdale described by me in 1856. It appears to overlie the mica slate, and thus confirms the view that the clay slates are the higher and newer formation. The part of the section, to which I wish especially to refer, lies further up the glen, and on to the Braemar mountains. The slates continue up Glen Beg to the foot of the steep pass over the Craig Well. Here a bed of bluish-grey limestone, with numerous veins of calc-spar, crops out, dipping at a high angle to the north-west. This is overlain by beds of gneiss passing up into quartzite, which forms the higher portions of the mountains."

The succession then in this region seems to be fairly well made out, and may be taken as under, in descending order:

4 Quartzite.
3 Blair Atholl Limestone.
2 Black Schist, with Tremolite Limestone near the top.
1 Ben Lawers Schists, with thin Limestone at the top.

It now remains for us to note briefly some of the principal features of the Upper Arenaceous Zone, the prominent member of which is the quartzite, to which reference has already been made. In this zone we have hitherto included the Blair Atholl Limestone, but it may be better in the future to place it at the top of the Upper Argillaceous Zone. It must be clearly kept in mind that although we have divided off the schists of the Highlands into a series of zones, they belong stratigraphically and physically to one great group of sediments, which pass into one another without any break. The only evidence of any break of importance is of that which occurs at the base of the quartzite group about to be described.

The quartzites and gneisses of Moine type, which constitute our Upper Arenaceous Zone, have been traced north-eastwards from the islands of Islay and Jura to the shores of Loch Awe, on the mainland, whence they spread over the whole of the region lying between the Caledonian Canal on the west, and a boundary line constituted by the northern limit of the Upper Argillaceous Zone on the east. We are not at present in a position to speak with any degree of assurance regarding the whole of this area, as we have not had an opportunity of examining it in any detail; but it seems to us that the quartzites which cover such a large part of it are undoubtedly those of Glen Lyon, Schichallion, and Ben-y-Ghloe, repeated over the whole of the area by isoclinal folding. The petrological character of the quartzite varies considerably in different areas. Thus in some parts it is very fine grained, with grey banding, while in others it is more massive, the individual grains of felspar and quartz being easily discernible by the naked eye. At times it is even pebbly (see Fig. 29).

We have already referred to the evidence pointing to the existence of a period of local erosion between the schists of the Upper Argillaceous Zone and the deposition of the quartzites of the Upper Arenaceous Zone. Upon this horizon there appears a very interesting deposit known as the Boulder Bed, which has

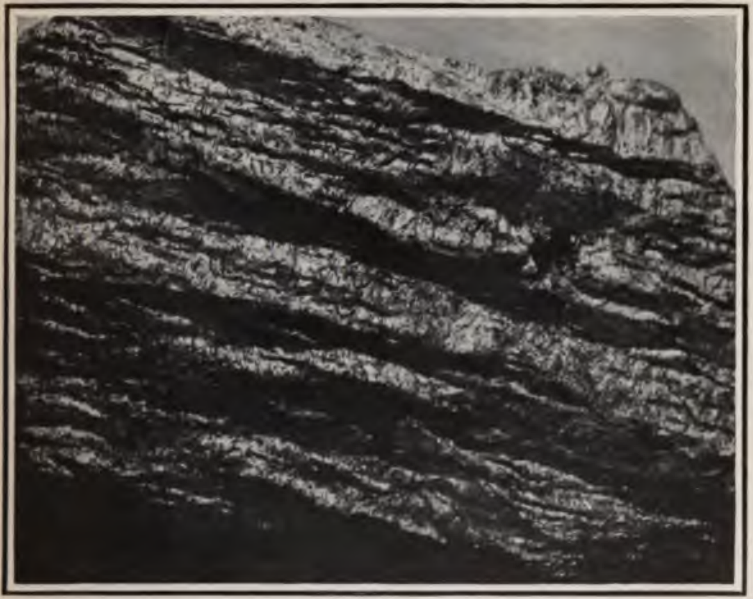


FIG. 27.—Ben Lawers Phyllite, Ben Lawers.

Photo. by W. LAMOND HOWIE, F.C.S.

been traced right across the heart of the Grampians from Braemar on the east to Islay on the west. It does not appear to be continuous, but makes its appearance here and there, at various points. The boulders in the Loch Awe district consist principally of quartzite and limestone set in a schistose matrix. These boulders vary in size from mere pebbles up to about two feet in diameter. In the Schichallion area, according to Mr. Barrow, the Boulder Bed is made up almost entirely of large boulders of granite.

Having thus described the geographical extent and leading petrological features of the different schist zones which constitute the Grampian geosynclinal, we now propose to discuss briefly their probable succession, thickness, and position in the geological scale—three very difficult questions, which can only be answered here in a very tentative manner. As regards the succession of the schist zones, we seem to be standing on fairly solid ground when we assert that it is an ascending one from the Lower Argillaceous Zone to the Upper Arenaceous Zone. This will, however, be better appreciated after we have examined the structure of the Grampians. In the meantime, it might be pointed out that as the rocks constituting the Lower Argillaceous Zone only appear in a narrow band across the Highland frontier, and do not reappear in the interior, it seems most likely that they are overlain by the other schist zones. Attempts have been made to correlate the Upper Argillaceous Zone with the Lower Argillaceous Zone, but this, we are afraid, cannot be maintained, great difficulties lying in the way of accounting for the position of the other schist zones which lie between them, while the lithological characters of the two zones are quite distinct. That the slates of the Lower Argillaceous Zone pass below the Ben Ledi grits, seems to be further supported by a fact recently pointed out by Mr. A. L. Du Toit. He says that in examining the records for the tunnel section of the Glasgow Water Works, he found that in several cases the bands of grit which are mapped on the surface have no representatives in the tunnel section, from which he concludes that they are only shallow outliers in the lower slate series. The whole structure of the ground between the great axial line of folding and the boundary fault points, we think, quite conclusively to the succession adopted here as being the correct one. Thus, we see the different schist zones coming apparently from beneath the great axial line of folding in simple outcrops, and being repeated in outliers between it and the great boundary fault. Again, we have no evidence of the existence in this area of such great lines of dislocation as we find in the north-west, which would tend to obscure and complicate the succession. So that, though the rocks have been extensively folded and refolded upon themselves, yet no actual rupturing has taken place; from which we conclude that, if once the general structure of the ground were unravelled and the character of the folding understood, we should stand on fairly solid ground regarding the order of succession.

The actual thickness of the different schist zones is also a point which might be better discussed after we have examined the structure of this region. In the meantime, we may simply state that the idea generally prevalent up to a comparatively recent time, which maintained that we had an enormous thickness of

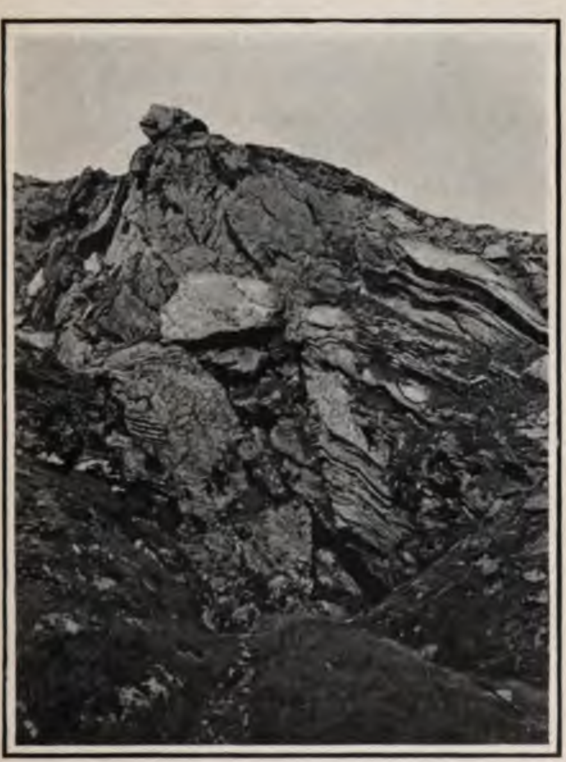


FIG. 28.—Folded Ben Lawers Phyllite, at summit of Ben Lawers.

Photo. by J. W. REOCH.

schists in the Grampian geosynclinal, has been gradually abandoned, now that the structure of the ground is being better understood. We see that a very thin bed, or series of beds, may be so folded upon itself, and that this folding may be of such a character, as to deceive one into the idea that he is dealing with thousands of feet of strata, whereas, in reality, the bed may not be any more than fifty or sixty feet thick. At present we are not in a position to give the actual thickness of the different schist zones. Nor can we see how this is to be accomplished without a very minute survey upon a large scale. Perhaps the officers of the Geological Survey may be able to throw some light upon this important subject, now that they recognize the existence of extensive folding, repeating comparatively thin beds. An interesting paragraph in this connection may be quoted from the Survey Report for last year. Speaking of one of the members of the Upper Arenaceous Zone (a band of porous quartzite which runs through Ben-y-Ghloe), the Report says: "Now the band, according to Mr. Barrow's observations, runs through almost every great quartzite mountain, and the evidence suggests that these three zones together form the greater part of the original mass. Ben-y-Ghloe is formed of quartzite, folded on itself to the exclusion of every other rock. The folds in this mountain are 2400 feet deep at least, and there is not a bend or buckle in the folds, while the bedding planes and limbs of the folds have a persistent dip of 60 degrees for nearly two miles."

Here, then, a thin bed of quartzite has been folded and refolded upon itself to such an extent as to form a mountain like Ben-y-Ghloe. Both the limbs of the isoclinal folds dip in the same direction at high angles without any evidence of minor folding, and we have a mountain apparently built up of thousands of feet of strata, whereas, according to Mr. Barrow, the band may not be more than twenty or thirty feet thick. Other equally striking examples of similar phenomena will be given later.

We pass now to what is admittedly the most difficult problem in connection with the schists of which the Grampians are built, namely, their age, or position in the geological scale. So obscure does the subject yet appear to be that we would almost prefer to pass it over in silence. The great difficulty arises out of the fact that as yet no organic remains have been found in these altered sediments, with the exception of the annelid tubes already referred to, and these, we are afraid, cannot be considered of much value in helping towards a solution of this problem. That the schists are older than the Lower Old Red Sandstone which lies to the south of the boundary fault, or which has been found here and there resting unconformably upon them, is made evident by the fact that the Old Red Sandstone conglomerates are often found to be made up of fragments of the older schistose rocks. Certain beds of conglomerate found in the Upper Silurian rocks of the South of Scotland have evidently been derived from the schists of the Highlands, which, of course, proves that the schists of the Highlands are not only older than these beds, but also that the metamorphism of the sediments of the Grampian geosynclinal, and the upheaval of the Grampian geanticlinal, must have taken place at an earlier period than the deposition of these Lower Old Red Sandstone, and Upper Silurian deposits.

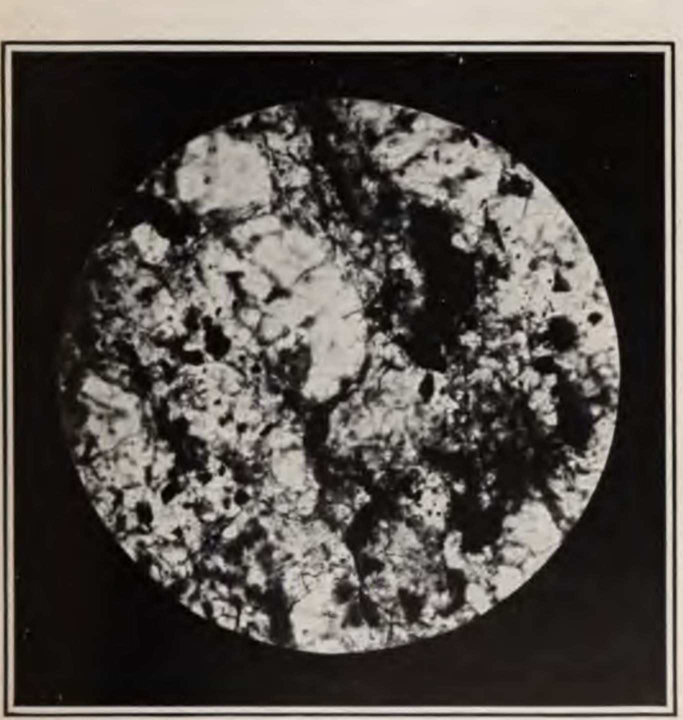


FIG. 29.—Quartzite. Falls of Tummel. (Magnified 25 dias.)

Photo. by JAS. B. CORR.

But exactly to what part of the early Palaeozoic period these schists belong, and whether they may not be Archaean, is a point which cannot at present be determined. If the schists of Moine type, which occur in the Upper Arenaceous Zone, could be definitely correlated with those of Sutherlandshire, and if the foregoing succession could be established with any degree of certainty, this would make all the other schist zones of a still older age than the Moine schists. The question, of course, still remains—what is the age of the Moine schists? It does not seem that at present we can give a very definite answer to this. That the Moine schists were originally of sedimentary origin, seems to be highly probable, as is evidenced by their peculiar granulitic structure, and the occasional traces of colour banding and false bedding, but no definite information has yet been obtained regarding their stratigraphical position. According to the Survey, the Torridon sandstones may have supplied the materials for the formation of these schists, and also, the Cambrian, or even later sediments, may have entered into the composition of the Moine schists. It will be seen, however, that these arguments are based on the assumption that the similarity of petrological character indicates the identity of the two groups of schists. How far this may be relied upon is a matter of opinion. All that we can say is, that it seems probable that they are identical, and that the Moine schists form an integral part of the altered sediments which constitute the Grampian geanticlinal.

CHAPTER V

THE METAMORPHIC ROCKS OF THE GRAMPIANS

2. Rocks of Igneous Origin

> Into the heart of all these great mountains, through every tossing of their boundless crests, and deep beneath all their unfathomable defiles, flows that strange quivering of their substance. . . . They, which at first seem strengthened beyond the dread of any violence or change, are yet also ordained to bear upon them the symbol of a perpetual fear. The tremor which fades from the soft lake and gliding river is sealed to all eternity upon the rock.
>
> Ruskin.

Amongst the schists and other altered clastic rocks of the Southern Highlands, which bear more or less evident marks of their original sedimentary origin, we find a series of schistose rocks whose origin has long been a subject of controversy, and whose exact nature and relationships have not even yet been fully disclosed. We refer to that class of rocks which has gone under the various names of epidiorite, hornblende-rock, hornblende-schist, primitive greenstone, and greenstone slate.

Maculloch, in his classification of rocks,[1] seems to

---

[1] *A Geological Classification of Rocks*, p. 298.

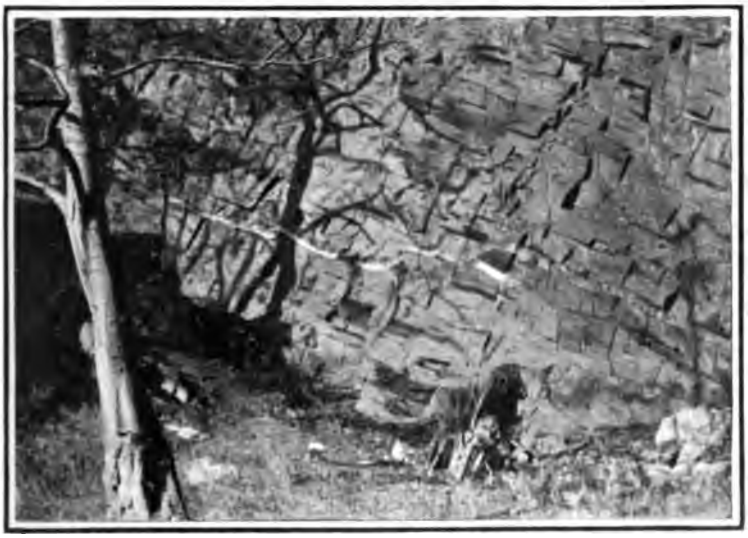


FIG. 30.—Balhoulan Quarry, Pitlochry, showing Hornblende-Schist, with Vein of Pegmatite.

Photo. by H. COATES.

have observed many of the distinguishing aspects of this rock, citing its occasional passage from the non-schistose to the schistose variety. He also notes that the former variety is always interstratified with the schistose one, and describes the association of hornblende-schist and chlorite-schist with many "anomalous compounds." This would seem to point to some of those schists being interbedded, and the chlorite-schists being the probable equivalents of contemporaneous volcanic tuffs. In speaking of its origin he says, "Whatever appearance of a mechanical disposition may arise from the occasional laminar alternation of the ingredients of this rock, . . . it is barely necessary to observe that the texture appears to be truly crystalline or chemical in all the varieties, and that it has not hitherto presented anything containing, like micaceous schist, decided fragments of other rocks." He thus seems to have looked upon it as one of the primary chemical precipitates from a thermal ocean.

De La Beche[1] further maintains the existence of a thermal ocean to account for the origin of these rocks, and thus describes it: "A time, however, must have come in the earth's history when the heated rock would merely allow the water to remain liquid upon it, and there would be a condition of things in which a great mass of heated water existed on the face of the globe, which, driven off by evaporation, condensed in the atmosphere, and fell again into the mass beneath. It was in this thermal ocean that such rocks as hornblende-schist were deposited." He further remarks that many of the inferior stratified rocks have evidently been chemical deposits, and some perfectly resemble granite and greenstone divided into beds. Some beds of hornblende rocks differ little from beds of greenstone. We have had opportunities of seeing how both these kinds of rocks pass in their lines of strike or direction into common gneiss or hornblende slate with mica.

---

[1] *Geological Researches in Theoretical Geology*, p. 298 *et seq.*

Sterry Hunt, in a later enunciation of this theory, says[1]: "As regards chemically-formed sediments, steatite, serpentine, pyroxene, hornblende, and in many cases garnet, epidote, and other silicated minerals are formed by a crystallization and molecular re-arrangement of silicates generated by chemical processes in the waters at the earth's surface."

Darwin[2] also points out the passage of greenstone into hornblende-schist, but he regards the greenstone as being the type of extreme metamorphism.

Prof. Jukes[3] seems to have been the first to consider hornblende-schist as being simply an altered tuff or basic lava, and makes the following remarks: "As far, indeed, as my own observation goes, I should doubt the existence of these rocks in any other form than as the result of a partial metamorphism of some hornblendic 'ash,' or of some mechanically-formed rock, derived from the wear and tear of a greenstone or a syenite."

Allport, Phillips, and Bonney, in our own country, and Lehmann, Lasaulx, and others on the continent,[4] have contributed more or less to the theory that these schists are nothing more than metamorphosed basic igneous rocks.

---

[1] *Chemical Essays.*

[2] *Geological Observations,* 2nd ed. p. 432.

[3] *Students' Manual,* p. 169.

[4] For papers by these authors, see *Quart. Jour. Geol. Soc.* v.y.

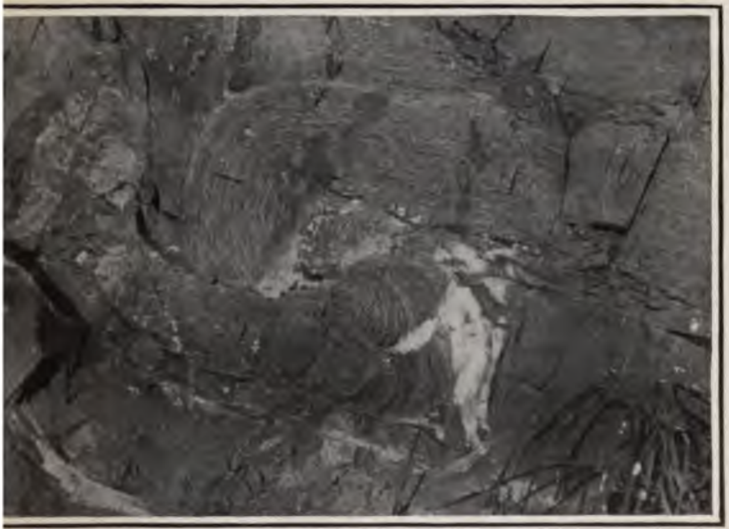


FIG. 31.—Folded Hornblende-Schist in Balhoulan Quarry, Pitlochry.

Photo. by H. COATES.

and greenstone divided into beds. Some beds of hornblende rocks differ little from beds of greenstone. We have had opportunities of seeing how both these kinds of rocks pass in their lines of strike or direction into common gneiss or hornblende slate with mica.

Sterry Hunt, in a later enunciation of this theory, says[1]: "As regards chemically-formed sediments, steatite, serpentine, pyroxene, hornblende, and in many cases garnet, epidote, and other silicated minerals are formed by a crystallization and molecular re-arrangement of silicates generated by chemical processes in the waters at the earth's surface."

Darwin[2] also points out the passage of greenstone into hornblende-schist, but he regards the greenstone as being the type of extreme metamorphism.

Prof. Jukes[3] seems to have been the first to consider hornblende-schist as being simply an altered tuff or basic lava, and makes the following remarks: "As far, indeed, as my own observation goes, I should doubt the existence of these rocks in any other form than as the result of a partial metamorphism of some hornblendic 'ash,' or of some mechanically-formed rock, derived from the wear and tear of a greenstone or a syenite."

Allport, Phillips, and Bonney, in our own country, and Lehmann, Lasaulx, and others on the continent,[4] have contributed more or less to the theory that these schists are nothing more than metamorphosed basic igneous rocks.

[1] *Chemical Essays.*

[2] *Geological Observations*, 2nd ed. p. 432.

[3] *Students' Manual*, p. 169.

[4] For papers by these authors, see *Quart. Jour. Geol. Soc.* v.y.

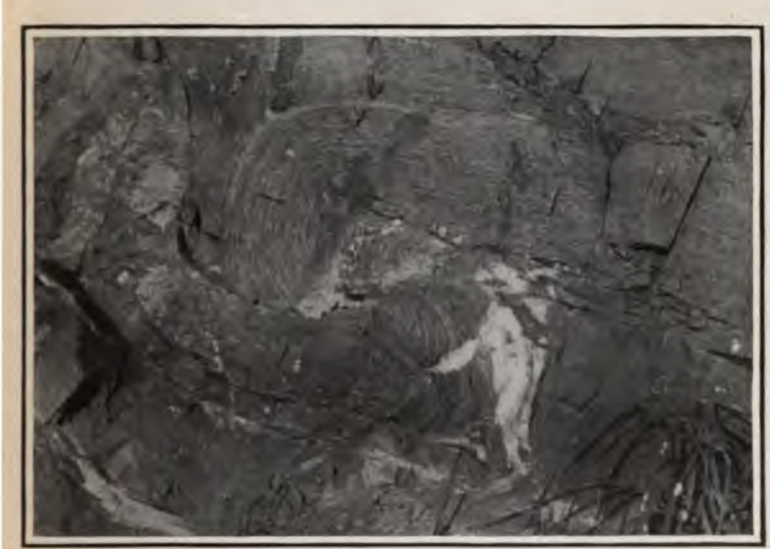


FIG. 31.—Folded Hornblende-Schist in Balhoulan Quarry, Pitlochry.

Photo. by H. COATES.

The idea of the metamorphism of a truly igneous rock into a highly-foliated schist had thus long been suspected, but it was not till the publication of Mr. Teall's paper on the Scourie dyke[1] that it was finally shown in a particular instance, in two dykes intruded into the old archaean gneiss of Sutherlandshire, where an undoubted passage was found from a crystalline dolerite into a hornblende-schist. The following may be taken as a summary of his conclusions: (1) That the hornblende-schist has been developed from a dolerite by causes operating after the consolidation of the dolerite, and that the metamorphism has been accompanied by a molecular re-arrangement of the augite and felspar; (2) That the molecular re-arrangement has in certain cases taken place without the development of foliation; and (3) That the plasticity which has led to the development of foliation is that due to high pressure at ordinary temperature.

In external appearance these altered basic rocks are almost always black, or at least of a very dark green colour. The proportion of felspar—one of its principal constituent minerals—tends to modify the dark colour more or less, and, when present in considerable quantities, gives the rock a dark greyish hue. Mineralogically it is a compound of felspar and hornblende, which are its essential minerals; but sometimes the hornblende may occur alone, there being infinite variations of the proportions between the two minerals (see Figs. 31 and 35). The rock is generally schistose, occurring in well-marked laminae of felspar and hornblende, but the degree of schistosity is very variable, passing from a high degree, through numerous alternations, to an entirely non-schistose variety—the primitive greenstone of early writers. Often the same bed will present in some of its parts one of these characteristics, while in others it will present that of an exactly opposite kind. The rock itself never forms large tracts in the Highland area, such as the clay-slates, quartzites, or mica-schists, but only occurs in subordinate beds alternating with some of the former rocks. Though the beds are thus only of moderate thickness (the sill in association with the Loch Tay Limestone being estimated at 200 feet in thickness), their extension along the line of strike or outcrop of the beds is often very persistent. The hornblende-schist commonly partakes of the contortions into which the other beds have been thrown, being bent and twisted in a similar way. It is always traversed by the granites and later intrusive igneous rocks of the Highlands, thus showing its anterior origin.

---

[1] *Quart. Jour. Geol. Soc.* vol. xli. p. 133.

The principal accessory minerals are pyrites and garnet, the latter sometimes occurring in quantities sufficient to modify the appearance of the rock. It is sometimes more or less perfectly crystallized as in mica-schist. In some rare cases, it is disposed in laminae amongst the hornblende (see Fig. 35).

Occasionally these schists show evidence of having been developed from a rock which had originally been highly porphyritic in character, the porphyritic felspar crystals being still recognizable, though now drawn out into long, more or less parallel, lines of shear. The original forms of the crystals have been, however, entirely lost, their faces having been completely rounded off during the process of the mechanical deformation of the rock. Occasional idiomorphic crys-

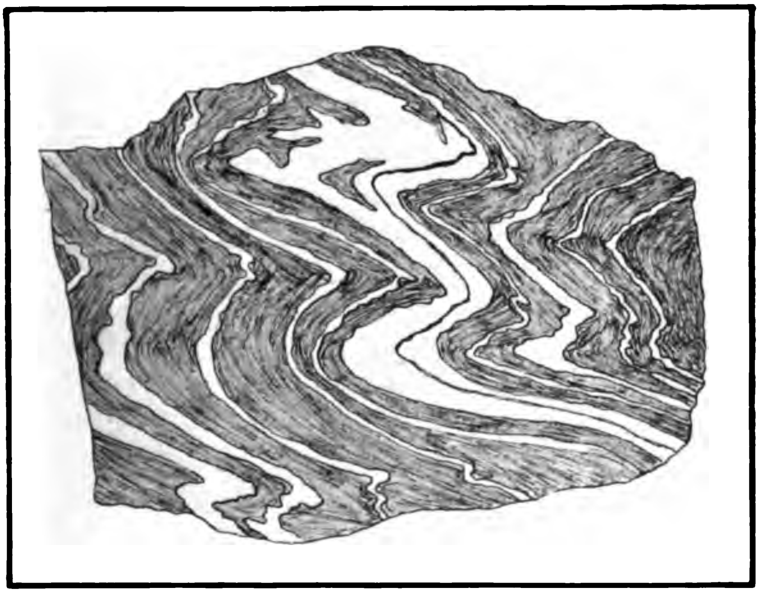


FIG. 32.—Banded Hornblende-Schist, Creag na Caillich.

tals appear, but as a rule they have been fractured or rounded at the edges to some extent. They lie imbedded in a highly sheared matrix of felspar and hornblende, and usually measure about a quarter of an inch in length.

Many of these schists show an extremely finely contorted, and foliated structure. In one hand specimen quite a series of these folds may be seen in the space of a few inches, it being equally as finely foliated and corrugated as any piece of typical mica-schist. In other cases the foldings are larger (see Figs. 31 and 32). In a hand specimen from the Loch Tay sill a piece of the original igneous or crystalline rock has been bent round into a perfect miniature syncline, or anticline, showing a completely schistose structure, the whole specimen measuring about 2 inches long by about 1½ inch wide.

One of the most interesting of all the specimens is that from the Loch Tay sill where it comes to the surface in Glen Lyon. The rock shows not only a highly foliated structure, but also a series of banded layers of felspar and hornblende. Now, when we consider that this banded structure (which would be quite easy of explanation in a clastic rock) belongs to what must have been at one time a basic igneous rock of ordinary crystalline texture, the problem of the banding becomes more difficult of solution. Mr. Teall, in a paper "On the origin of certain banded gneisses," proposes to account for the origin of a banded structure in a rock originally crystalline. He there shows[1] (1) that banded gneisses are on the whole identical with plutonic rocks in composition; (2) that masses of plutonic rocks are often heterogeneous; and (3) that heterogeneous masses, if such exist, may be deformed in the manner required to produce banded structures (see Fig. 33). He illustrates his case experimentally by showing how if two pieces of differently-coloured clays be mixed up together and then drawn out to imitate a shearing process, folded over and then drawn out again, a perfect banded structure will be produced in the clay. He sums up by saying: "It may be a long time before we become acquainted with the precise nature of the movements and deformations, but that they are adequate to convert a heterogeneous mass into a banded gneissic series is, to say the least, highly probable." Our own opinion is that these banded structures in hornblende-schist are probably referable to a somewhat similar process to that brought forward to account for the banded gneisses of the Lizard district by Mr. Teall.

---

[1] *Geological Magazine*, 1887.

Fig. 32 is a diagrammatic representation of a hand specimen of banded hornblende-schist from near Cashlie in Glen Lyon, the dark banding being mainly composed of long prisms of hornblende arranged according to the general schistosity of the mass, while the white bands represent layers of felspar.

An examination and comparison of a specimen of porphyritic hornblende-schist with this banded specimen will, we think, throw some light upon the origin of the latter. In the process of the mechanical deformation of the original crystalline rock the porphyritic crystals of felspar are seen to be arranged in linear streaks parallel to the general schistosity of the rock. Now, we do not think it would be difficult to imagine how, under certain conditions, this porphyritic hornblende-schist would pass into a truly banded type, as

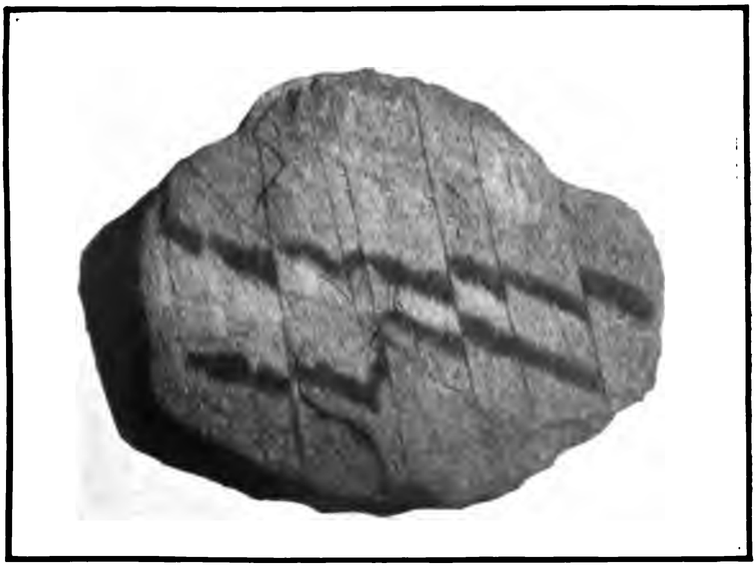


FIG. 33.—Banded Hornblende-Schist, with Reversed Faults, Pitlochry.

Photo. by WM. ELLISON.

seen in the specimen from Glen Lyon. The existence of the felspar crystals fulfils the condition of making it a heterogeneous mass, and we look upon the banded specimen as a further deformation of such a rock as the porphyritic hornblende-schist.

Passing now to a consideration of the microscopic structure of these rocks, they are shown, under a low power, to be built up of alternating folia of light and dark material, which, with an increased power, are resolved into layers of felspar and hornblende. The felspar, has, in most instances which we have examined, except in the case of the porphyritic hornblende-schist, entirely lost its original structure, and has become deformed by the breaking up of the original felspar crystals into a finely granular mass.

The grains of felspar, with which may also be associated some quartz and epidote, are in most instances perfectly water-clear, and, so far as the rock structure itself is concerned, give more the appearance of a clastic rock, such as quartzite, than of an originally crystalline mass (see Fig. 35). So complete is this simulation of a clastic rock, that it deceived, for a considerable time, not a few experts in petrology.

In the porphyritic hornblende-schist the large crystals of felspar do not seem to have suffered so much as those in the ordinary types of the rock. Parts of the crystals have been broken down into a granular mass, in which are imbedded laths of hornblende. Portions of them, however, seem to have escaped this deforming process, and still retain the original twin striations so characteristic of the plagioclase felspars, and even in some instances, as we have already pointed out, the form of the crystal itself. These grains of felspar show a distinctly parallel or linear arrangement along the lines of shearing in the rock, the longer axes of the grains generally all lying in the same direction. The hornblende occurs as long needles or prism-shaped forms, in thin sections, showing a bright green colour passing into brownish shades, the latter probably owing to weathering. As a rule, the longer diameter of the needles, or prism-shaped forms, lies parallel to the plane of schistosity. On rotating the polarizer the hornblende displays a marked pleochroism.

In a paper "On some schistose greenstones and allied hornblende-schists from the Pennine Alps as illustrative of the effects of pressure metamorphism,"[1] Professor T. G. Bonney refers (in a foot-note) to the occurrence of this Scottish porphyritic hornblende-schist. He says: "Since the above paper was written I have obtained additional evidence from Scotland. In the Pass of Killiecrankie dioritic dykes, more or less schistose, are frequent, some of which present interesting resemblances to certain of the Alpine hornblende-schists. The rocks can be examined *in situ*, close to the Garry, and occur as boulders in its channel. They are more or less foliated, evidently sometimes containing biotite, and not unfrequently red garnet. Occasionally the former presence of a porphyritic felspar is indicated by white spots. In other parts of the same mass garnets are abundant. (I have long suspected that most eclogites are diorites in which garnet has taken the place of felspar.) I have examined microscopically one of the less foliated examples from a dyke above the bridge in the village, and the most foliated one from a boulder. Both, especially the

---

[1] *Quart. Jour. Geol. Soc.* 1893.

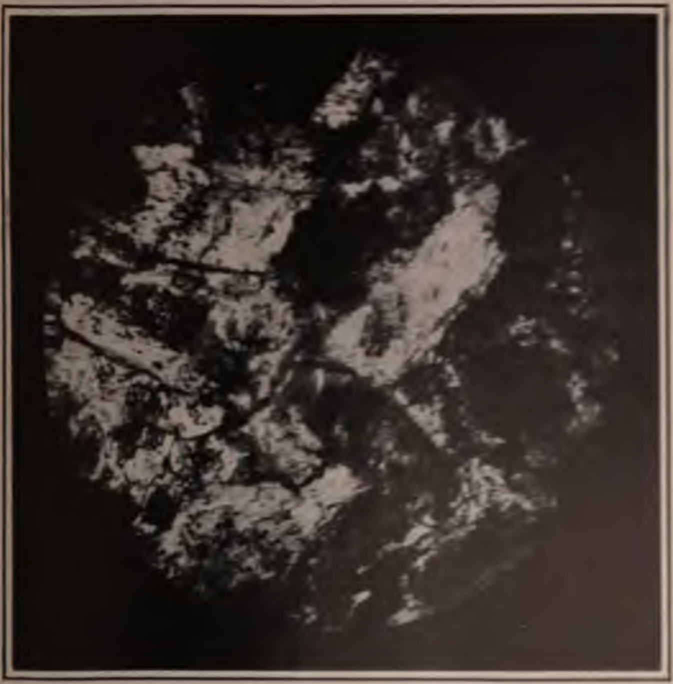


FIG. 34.—Epidiorite, Creag na Caillich. (Magnified 40 dias.)

Photo. by JAS. B. COWE.

latter, strikingly correspond with some of the rocks described in this paper, the hornblende occurring in dark green prisms with enclosures evidently of later date than that of the principal crushing—the biotite being newer than the hornblende and sometimes suggesting pseudomorphic replacement, and the garnets being anterior to the crushing."

Mr. Teall[1] thus describes a porphyritic hornblende-schist or porphyritic epidiorite, which he supposes to have been originally a porphyritic dolerite: "In thin sections the ground mass of the rock is seen to consist of long actinolitic needles, water-clear grains of felspar, and grains of leucoxene. The needles are arranged approximately parallel to each other in the plane of schistosity (direction of stretching). The water-clear substance is certainly in many cases biaxial, and therefore may with considerable confidence be referred to felspar. It may be said in a certain sense to play the rôle of ground mass, for actinolitic needles often lie imbedded in it. Grains of a nearly opaque substance, in part brown granular sphene, evidently represent the iron ores of the original rock. The eyes of the schist are turbid felspar pseudomorphs similar to those which occur in the epidiorites. Their angles have, however, been completely rounded off." Thus, this description of the hornblende-schists of the Lizard exactly corresponds with those from the Highland area which we are now considering.

In Glen Lochay, about three miles from the foot of the glen, a bed of serpentine crops out on its southern side amongst the mica-schists, and was mined for chrome iron ore by the late Marquis of Breadalbane. The serpentine is of a dark green colour, mottled with lighter shades. The chrome iron ore is disseminated through the serpentine in grains, and with it are associated steatite and cryolite. Like the epidiorites, it has been intruded into the schists as a basic igneous rock prior to their metamorphism (see Fig. 36).

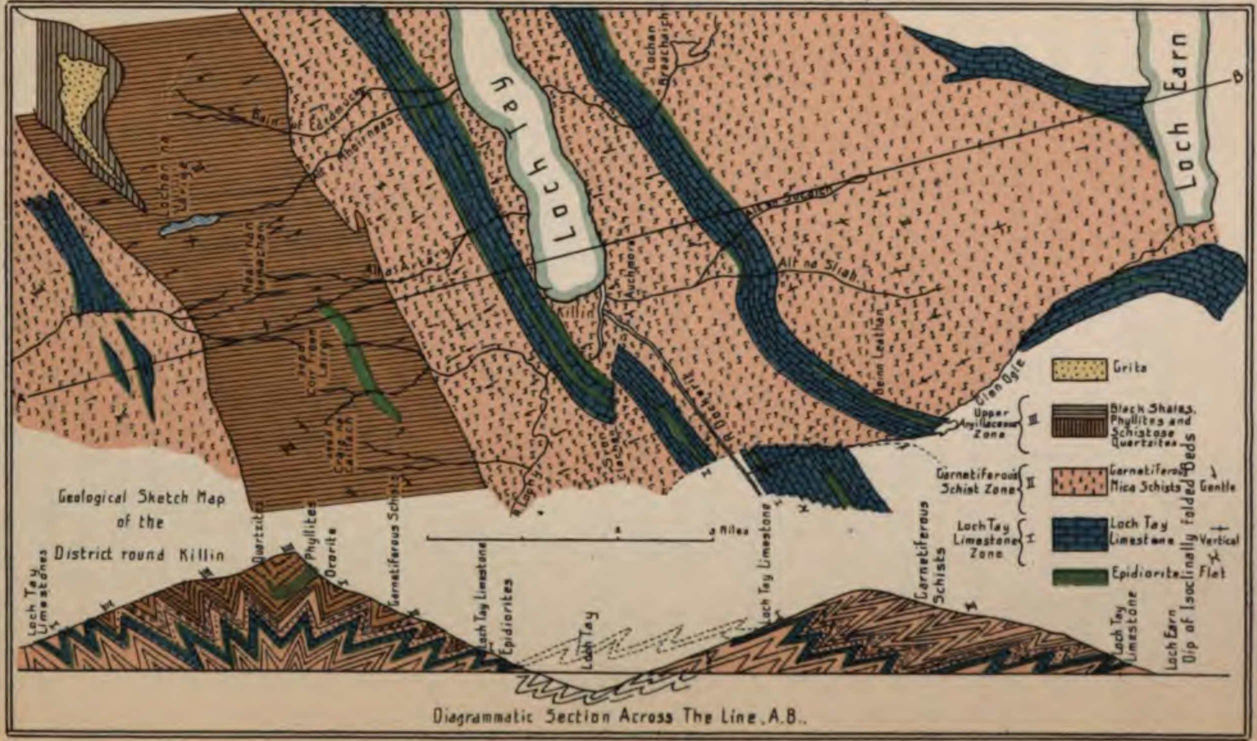
---

[1] *Proceedings of Geologists' Association*, "Excursion to Cornwall," August, 1887, p. 41.

To what species of the basic igneous rocks these hornblende-schists may have originally belonged it is often difficult to say. The presence of porphyritic crystals of felspar still showing the characteristic twin striation of the plagioclase group, and the large percentage of hornblende in the schist, which has been shown to have an intimate relation with augite, would lead us to infer that the rock had originally been intruded as some variety of diorite. Some of these hornblende-schists may be allied to the gabbros, which are also found as intrusive sills in the Southern Grampians, as in Glen Quaich near Crieff; and, according to the Geological Survey, many of the massive epidiorites of Glen Fernate can be shown to have been originally ophitic gabbros.

Dr. Lehmann has described many instances of the passage of a gabbro into a hornblende-schist in the granulitic region of Saxony by powerful mechanical strains, and Teall has applied the same explanation to the gabbros of the Lizard, showing how the original rock, composed of labradorite or bytownite, has passed with the development of foliation into a schist, the felspar passing into saussurite, and the augite into hornblende.

Before passing to a description of the particular bed of hornblende-schist which accompanies the Loch Tay



Geological Sketch Map of the District round Killin

Diagrammatic Section Across The Line, A.B..

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS.

Limestone, and which we propose to take as an illustration of its mode of occurrence in the Highlands, we shall again briefly revert to the structure of the latter—and the general distribution of these sills of hornblende-schist through the undoubted clastic rocks (see Sketch Map facing p. 138).

We have proposed to group the altered clastic rocks of the Southern Grampians in the following order, beginning with the uppermost and youngest members of the group:

1 The Upper Arenaceous Zone.
2 The Upper Argillaceous Zone.
3 The Garnetiferous Schist Zone.
4 The Loch Tay Limestone Zone.
5 The Lower Arenaceous Zone.
6 The Lower Argillaceous Zone.

The lowest member of the series is that well-known band of clay-slate which passes from shore to shore of the island, outcropping at the southern verge of the Highlands. The next above, or Lower Arenaceous Zone, is composed of a massive series of grits, greywackes, and conglomerates, well seen in Ben Ledi, the Pass of Leny, and Ben Vorlich. According to Sir Archibald Geikie and his colleagues of the Geological Survey, it is at the top of this group that hornblende-schists first appear in the Highland rocks. Passing upwards into the Garnetiferous Schist Zone, they become quite common, being well seen in the massive sill underlying the Loch Tay Limestone. In the Upper Argillaceous Zone and Upper Arenaceous Zone hornblende-schists are also locally abundant. It seems, then, they are to be found more or less commonly in all the zones, excepting the Lower Arenaceous and Lower Argillaceous group. How they should be absent from these latter, more especially when they are considered to be as originally of intrusive character, is a problem I am unable to solve.

Intercalated in our Garnetiferous Schist Zone is a series of bands of limestone and calcareous mica-schist, to which has been given the name of the Loch Tay Limestone Zone from its great development in that district. On the north side of Loch Tay this band of limestone comes to the surface at Killin, and is well seen in a bold escarpment on the south front of Sron Clachan, crossing underneath the eastern slope of the latter mountain. It has been levelled down by the passage of the river Lochay into Loch Tay, but again rises in extensive precipices in the woods of Finlarig, from which it passes north-eastwards in a straight line along the bases of Meall nan Tarmachan, Ben Ghlas, and Ben Lawers, to Fernan, where it is cut off by a powerful fault. The limestone dips underneath the group of mountains forming the northern sides of Loch Tay at an angle of about 45° to the north-west (see Coloured Sketch Map, p. 138).

On the south side of the loch the limestone is seen high up on the side of Ben Leathan, from which point it may be traced round to the head of Glen Ogle, where it will be found near the old Killin junction. Passing down Glen Ogle, the limestone may be observed at various points, till, on reaching Loch Earn, it curves round to the east, again being well exposed in Dalveich quarry. From this point it extends north-eastwards up Glen Beich into the basin of the Tay again. An isolated outlier of the Loch

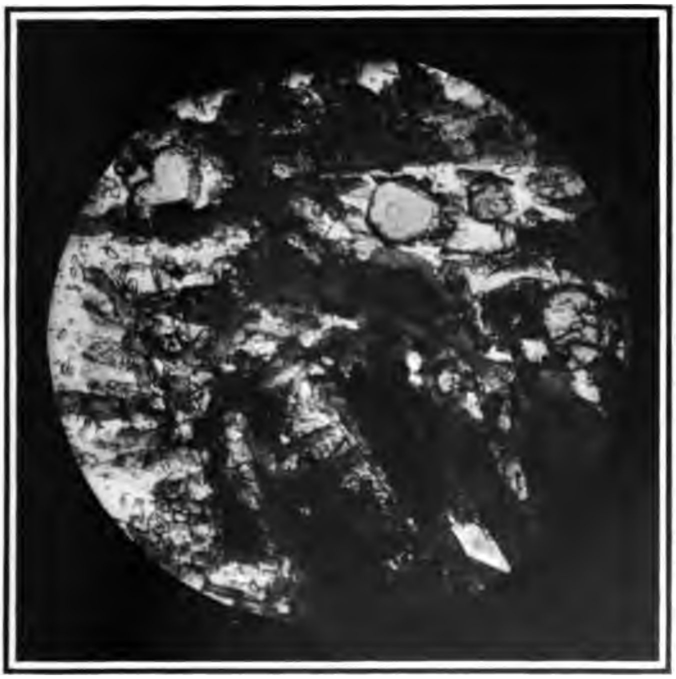


FIG. 35.—Hornblende-Schist, Loch Tay. (Magnified 40 dias.)

Photo. by JAS. B. CORR.

Tay Limestone is also seen to cap the top of Meall na Creige, a mountain 2683 feet high, on the south side of the loch.

We have thus somewhat minutely defined the range of the Loch Tay Limestone, because it is a singular fact that wherever it outcrops to the surface it is found to be followed by a band of hornblende-schist. In the Finlarig woods at Killin, and on the pier road there, some very fine sections of the hornblende-schist and limestone in actual contact are to be found. So close and so well defined is this line of contact that the blade of a pocket knife could be inserted between the two rocks. This band of hornblende-schist is seen to follow the limestone in its course along the north side of Loch Tay, as already described. On the south side of the loch a similar occurrence of limestone and hornblende-schist is to be seen. Tracing them down Glen Ogle, the limestone and the hornblende-schist are found outcropping together in the bed of a stream a little to the north of the Glen Ogle toll-house. Passing round into the valley of the Earn a very fine section of the hornblende-schists and the limestones is exposed at the foot of Glen Beich, the contact of the two rocks being traceable right to the head of that glen and back into the valley of the Tay. Underneath the outlier of limestone on the summit of Meall na Creige the hornblende-schist is also seen.

In the map of the Loch Tay district and accompanying section, the blue band represents the outcrop of the limestone, while the green band is that of the hornblende-schist outcropping at the base of the former wherever it is exposed.

Sir A. Geikie, speaking of this sill in his Presidential Address to the Geological Society of London,[1] says: "Over wide tracts of the central and south-western Highlands, and of Donegal, some of the most marked and persistent rocks are sheets of diorite, epidiorite, and hornblende-schist, which were erupted as molten materials, not improbably as varieties of diabase lava. Most of these sheets are doubtless intrusive sills, for they can be observed to break across from one horizon to another. But some of them may possibly be contemporaneous lava streams."

A sheet may sometimes be traced for many miles occupying the same stratigraphical platform. Such hornblendic rocks occur on many horizons between the great band of Ben Vorlich grits and the Ben-y-Ghloe quartzite. One of the most marked of these is a sill, sometimes 200 feet thick, which underlies the Loch Tay Limestone. In Argyllshire also an abundant series of sheets of epidiorite, amphibolite, and hornblende-schist runs with the prevalent strike of the schists, grits, and limestones of that district, while similar rocks re-appear in a like position in Donegal. The frequency of the association of these eruptive rocks with the limestones is worthy of remark.

It might be inferred from the manner in which this bed of hornblende-schist comes so constantly to the surface with the Loch Tay Limestone that it must originally have been a contemporaneous bed of igneous rock rather than an intrusive sill. But in various sections, and more particularly in that exposed near Killin, at Finlarig, the hornblende-schist undoubtedly transgresses the beds of limestone, the latter being

---

[1] *Quart. Jour. Geol. Soc.* 1891.

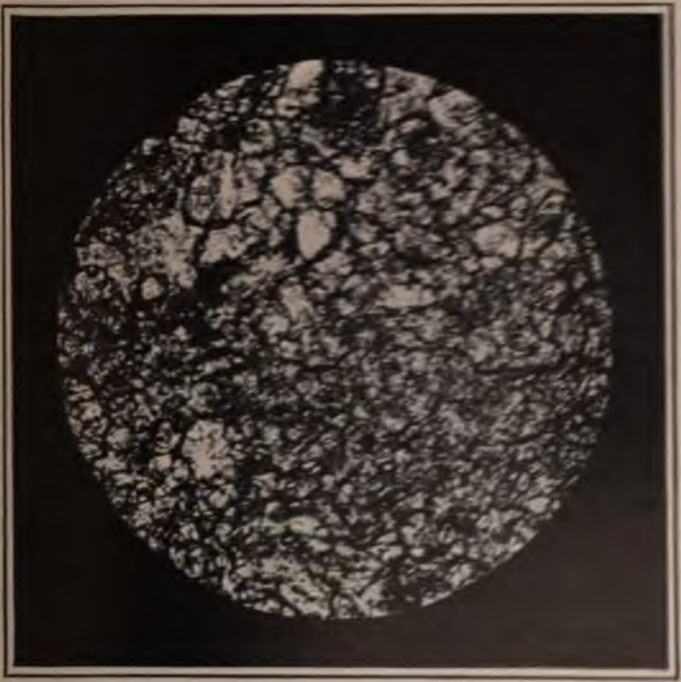


FIG. 36.—Serpentine, Corrycharmaig. (Magnified 25 dias. Crossed Nicols.)

Photo. by JAS. B. CORN.

baked and altered in the manner characteristic of contact with an intrusive igneous rock.

We cannot here enter into the problem of the manner in which these sills of intrusive igneous rocks attack and keep so constantly to one stratigraphical horizon. That they are capable of doing so is, however, well known—a more recent instance being the remarkable whin-sill of Teesdale, Northumberland, of which Messrs. Topley and Lebour have demonstrated the undoubted intrusive origin. The process may be chemical as well as mechanical, the intrusive mass gradually replacing the invaded rock by assimilation; and, if this be true, it may also account for the manner in which these hornblende-schists are so often found associated with the limestones.

These epidiorites and hornblende-schists make their appearance upon other horizons as well as that of the Loch Tay Limestone. Thus, a sill almost invariably appears at the base of the Ben Lawers phyllites or Upper Argillaceous Zone. This sill is well exhibited on the ridge north of Loch Tay, where it often shows a fine parallel banding. It has also been traced in the ground north of Pitlochry, and between the Tummel and Glen Brerachan, where it is seen to be intimately folded with its accompanying clastic schists. The Garnetiferous Schist Zone, which overlies the Loch Tay Limestone, and the schists which immediately underlie the limestone, also contain numerous sills of epidiorite. The Lower and Upper Arenaceous Zones appear to be comparatively free from such intrusions. A sill of epidiorite, however, occurs along with the black shales and cherts, seen along the Highland border to the west of Aberfoyle.

Mr. Barrow of the Geological Survey has pointed out that in Ben Vrackie there can be seen the source of a great sill of epidiorite, which occupies a horizon between the Ben Lawers phyllites and the overlying black schist (see Fig. 37). According to Mr. Barrow, it takes the form of a large flattened laccolite, spreading out into a sill, which thins out rapidly to the south and south-west, but less so to the north. The high ground at Ben Vrackie is due to the folding of this great igneous mass with the underlying Ben Lawers schist. Only one intrusion appears to have taken place, and the rent or pipe, through which the igneous material was introduced, cannot be located with certainty, but may be looked for on the south-eastern or south-western face of Ben Vrackie, where the intrusion is thickest. The laccolite has not been subjected to the rapid isoclinal folding seen in the surrounding rocks, being in all probability too thick and massive to be so affected. It is bent into great rolling flexures, between which the underlying or overlying rock is intensely folded. Where, however, the laccolite is represented by a comparatively thin sill, it has shared in all the folding of the surrounding rocks.[1] The hornfelsing of the strata in contact with this laccolite

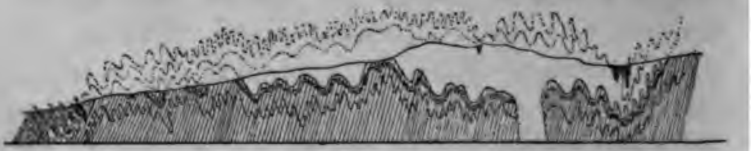
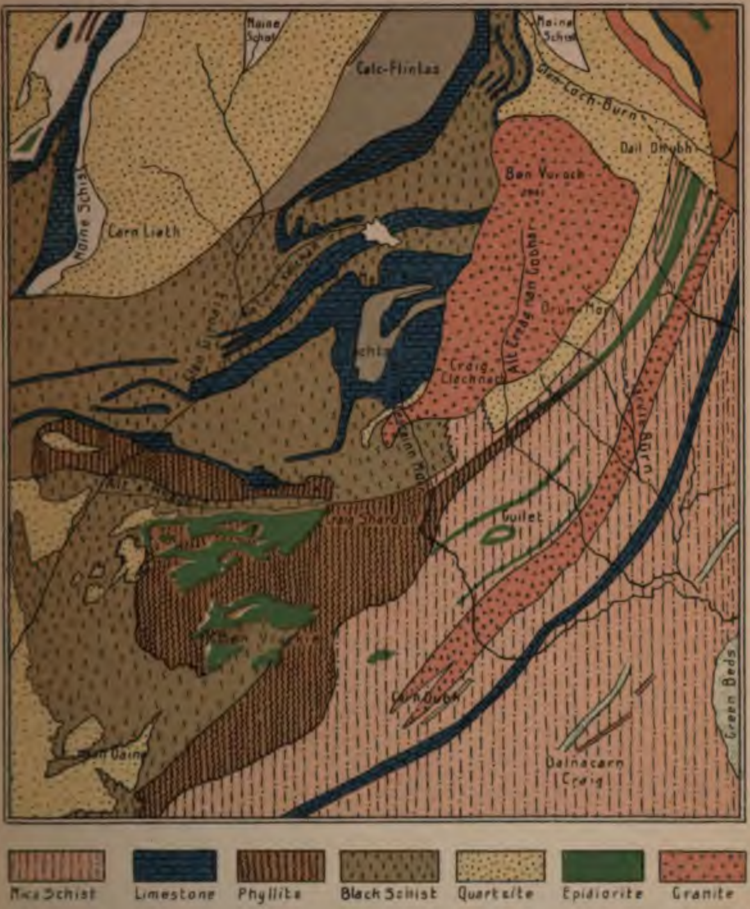


FIG. 37.—Diagram Section through Ben Vrackie, showing Sill of Hornblende Schist.

---

[1] *Memoirs of the Geological Survey.* "The Geology of the Country round Blair Atholl, Pitlochry, and Aberfeldy," p. 77.



Geological Sketch Map of the District round Ben Vuroch.

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS.

can be distinctly seen in many places on the summit and south-eastern slopes of Ben Vrackie. This is best observed where the igneous rock comes in contact with the black schist, which is there seen to be baked and indurated for a distance of at least 20 yards from the point of contact. Near its centre, the laccolite has all the appearance of a massive plutonic rock, and shows little or no signs of schistosity. It is composed principally of hornblende in two generations, granular felspar, and epidote, with occasional patches of sphene. At the margin of the sill the rock passes into a true hornblende-schist, showing a well-marked foliation.

Besides these basic igneous rocks, which have clearly been intruded as sills among the clastic schists prior to the general metamorphism which has affected this region, there occurs in the north-east of Perthshire a large intrusion of granite, which has also evidently taken place prior to the period of metamorphism. Many clear sections can be seen, showing a passage from a normal granite into a foliated granite or gneiss, revealing well-marked eye structure (augen-gneiss). The area occupied by this intrusion lies about six miles to the north-east of Pitlochry, and is situated between Glen Girnaig and Glen Fernate. It rises near the head-waters of these streams in Ben Vuroch, a mountain having an altitude of nearly three thousand feet above sea level (see Sketch Map).

With the exception of a narrow border, the main mass of Ben Vuroch consists either of granite or granitoid gneiss. Near the summit of the hill the gneiss exhibits *Augenstructur*, but becomes more micaceous and schistose as it is traced towards the foot. On the western side of the mountain, numerous areas of unfoliated granite may be met with, yet, as a rule, there are few tracts of any considerable size that do not show some traces of foliation. A remarkable series of parallel crush planes forms a conspicuous feature near the summit of the hill. These all trend in a N.N.E. and S.S.W. direction, and dip at an angle of 60° to the E.S.E., and it is to the movements that have produced these crushes that the gneissose structure of the granite is due. In the neighbourhood of Loch Valican the intrusive character of the granite is well shown by the manner in which the vertically folded limestones and black schists of the upper Argillaceous Zone strike against the igneous rock.

Where the granite shows least signs of alteration it is seen to be composed of the usual ingredients—felspar, quartz, and brown mica, the felspar being the most abundant constituent. In this section, both orthoclase and plagioclase are seen to be present, the former showing the typical cross striation of microcline, while the plagioclase felspar, which is mostly oligoclase, shows a more or less perfectly developed polysynthetic twinning. The quartz presents the usual characteristics of this mineral, as seen in granite, and appears to belong to two generations, the presence of numerous minute inclusions giving it a dusky appearance. The brown mica occurs both in small isolated flakes and aggregations and in large irregular shaped crystals, and contains inclusions both of zircon and sphene. Here and there, garnet occurs as an accessory mineral.

In the foliated portions of the rock a well-marked *Augenstructur* is exhibited, the mineral constituents being seen to sweep round eyes of felspar, which are rounded at one end and tapered off at the other. The broader part of the eye consists of potash-felspar, while the rounded end shows it in contact with some other mineral, usually quartz. The tapering end or tail consists, for the most part, of the felspar of the eye, which has become broken down. The brown mica usually forms part of the *flaser* material that is seen to wrap round the eye. The altered granite also contains a considerable quantity of white mica, which has been developed by the recrystallization of the microcline. Secondary garnet also occurs in considerable quantity. The rock is holocrystalline, and the absence of strain shadows in the minerals shows that it has become entirely recrystallized. According to Mr. Barrow, two facts are established by the consideration of the evidence furnished by the foliated granite of Ben Vuroch and the surrounding sedimentary strata. First, the present character of the splintery rocks in the north-west flank of Ben Vuroch shows that they could not have existed as crystalline schists at the time when that mass was intruded. Second, that the occurrence of certain pegmatites in the area to the north-east of the Ben Vuroch granite, derived from the muscovite-biotite magma, and free from all foliation, shows that the crystallization of the schists was practically complete before the consolidation of these pegmatites. Hence Mr. Barrow considers that the foliated character of the Ben Vuroch granite, which consolidated before the movements began, is due to cataclastic influences.

In Glen Tilt there are other two localities where these older granites are exposed at the surface, namely, Meall Gruaim and Clachghlas. They resemb

Ben Vuroch granite in original composition, and affinities of the augen-gneiss in both localities be easily recognized. The Glen Tilt intrusio however, present certain structural and mineralog differences which have been described in consider detail in the explanation of sheet 55 of the *Geolog Survey Memoirs.* We would refer the reader in sear of further information upon these rocks to that wo Other localities where these older intrusions of gran are exposed, are Carn Dubh, about four miles nor east of Pitlochry, and Dunfallandy Hill, two mi to the south of Pitlochry.

An area, such as the Highlands of Scotland, ma be looked upon as a petrological complex, in whic prior to its metamorphism, all kinds of igneous an sedimentary rocks were represented, just as the Ol Red Sandstone, or Carboniferous series, with their associated igneous rocks, can be seen at the present day. But, owing to earth-strains, these originally horizontal rocks have been plicated into a complex system of compressed folds, graduating from fan-shaped structures many miles in width, down to the finest corrugations to be seen in a hand specimen. A metamorphic area is simply a petrological complex upon which a universal foliation has been superinduced by pressure. This foliation generally lies parallel to, or is related to, the direction in which its component strata of rock have been piled up.

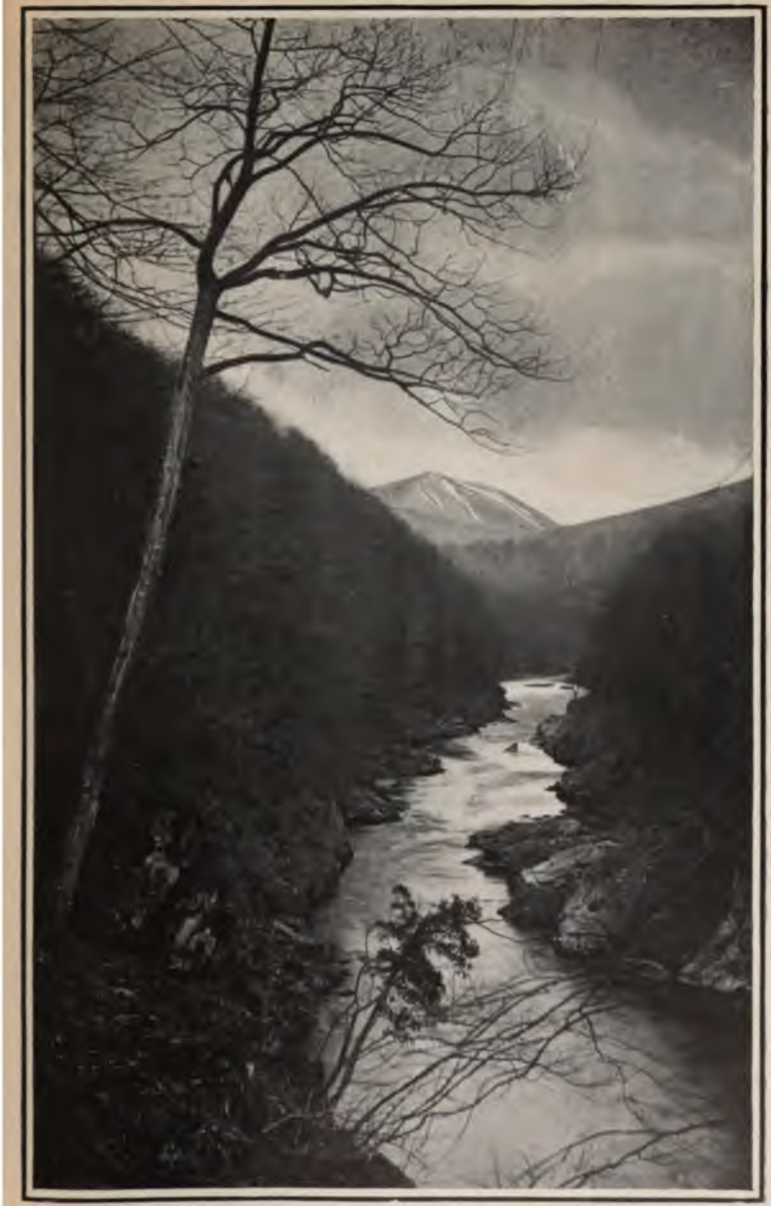


FIG. 38.—Pass of Killiecrankie, and Ben-y-Ghloe.

Photo. by WM. ELLISON.

CHAPTER VI

THE GEOLOGICAL STRUCTURE OF THE GRAMPIANS

> Ages are thy days,
> Thou grand affirmer of the present tense,
> And type of permanence!
> Firm ensign of the fatal Being
> Amid these coward shapes of joy and grief,
> That will not bide the seeing!
>
> Hither we bring
> Our insect miseries to thy rocks;
> And the whole flight, with pestering wing,
> Vanish, and end their murmuring,—
> Vanish beside these dedicated blocks,
> Which who can tell what mason laid?
>
> EMERSON.

TURNING now to a consideration of the structure and development of the Grampian geanticlinal, as it is seen in the Southern Highlands, we propose, in the first place, to examine briefly some of the first principles of mountain building, as developed by Professors Heim and Lapworth. The evidence, derived from the study of the Grampian geosynclinal, shows us that for a long period the site now occupied by the Grampians had been covered by the sea, and that a considerable extent of sediments, consisting of shales, sandstones, grits, conglomerates, and limestones, had been slowly accumulated. These sediments would be accumulated in a more or less horizontal position, as the trough in which they were formed would be comparatively shallow. A time would eventually ensue when the sinking of the geosynclinal would be arrested, and the strata of which it was formed would be forced upwards. I do not here propose to make any detailed inquiry into the nature of the forces which produced this elevation and plication of the original horizontal strata; but, assuming that the crust of the earth is in a constant state of compression, and that this compression, steadily acting upon the mass of accumulated sediments, would set up a series of tangential thrusts, which would eventually plicate the strata into innumerable arches and troughs, then, as a consequence of this folding of the strata, the rocks would be compressed into a much narrower horizontal space than that which they originally occupied. The character of the folding would, of course, depend upon the intensity of the pressure. Where the pressure had been comparatively slight, the folding would also be comparatively simple. In the heart of the mountain chain, where the pressure had reached its maximum of intensity, the folding would be much more acute; inversion and reversed faults would be produced, and all the phenomena seen in such highly convoluted mountain regions would be developed.

Fig. 39B is a diagram after Bailey Willis, which illustrates the formation of the Grampian geosynclinal. Upon the old continent of Archaean gneiss, the sedimentary rocks of the Highlands were laid down in an approximately horizontal position. Fig. 39A shows the manner in which the geanticlinal has been ridged up into a series of anticlinoria and synclinoria.

Another result of the plication of these rocks is the extensive metamorphism which they everywhere exhibit. Like the folding, the intensity of the metamorphism would range according to the amount of pressure to which any particular area had been subjected. Towards the core of the geanticlinal, and where extensive folding and crushing had taken place, a corresponding increase in the metamorphism would naturally be looked for. It would be found that the rocks in this particular area had become more completely deformed than those in which the pressure had been less intense. Secondary, tertiary, and even quaternary structures

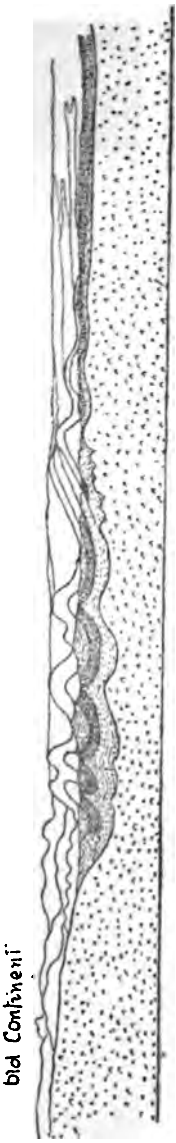


FIG. 39 A.—Diagram to illustrate the formation of the Grampian Geanticlinal.

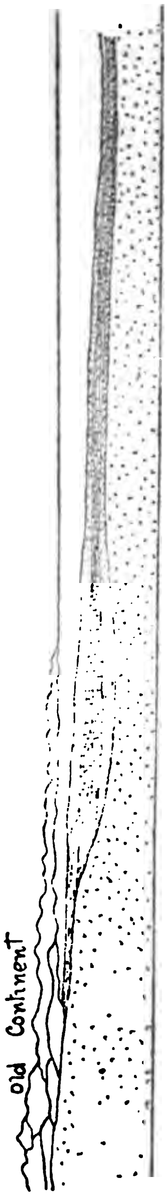


FIG. 39 B.—Diagram to illustrate the formation of the Grampian Geosynclinal.

would be developed, while such secondary minerals as garnet, mica, hornblende, apatite, etc., would be produced. Beginning, then, with the assumption that the strata forming the Grampian geosynclinal had been laid down in a more or less horizontal position, we find that, owing to a series of tangential thrusts and counter-thrusts, the original horizontal strata have been bent into a number of folds. Where pressure has been slight these folds belong to a simple type, though we question whether any of these simpler forms of folding are to be seen in the Grampians. Nevertheless, as it is likely that the present more complex folding may have originated in the simpler types, the latter ought to be first described. Fig. 41 represents a fold of the simplest type. It is seen to consist of two opposite and symmetrical members, respectively known as the upward bend or arch, and the downward bend or trough, the part connecting the arch and trough being designated the middle limb. The crest of the upward fold is called the arch bend, while the corresponding part in the downward fold is named the trough bend. The other parts of the fold, such as the arch limb and arch core, trough limb and trough core, will be best understood by a reference to Fig. 41.

Where the pressure has been comparatively slight, folds of the type just described would be produced, in which case the axes of the folds would be approximately vertical, and the beds dip in opposite directions. These have been designated normal flexures or amphiplexes, and the strata bent in this simple form orthoclinic or amphiclinic strata (see Fig. 42, *a*).

With an increase of the lateral pressure, these simple

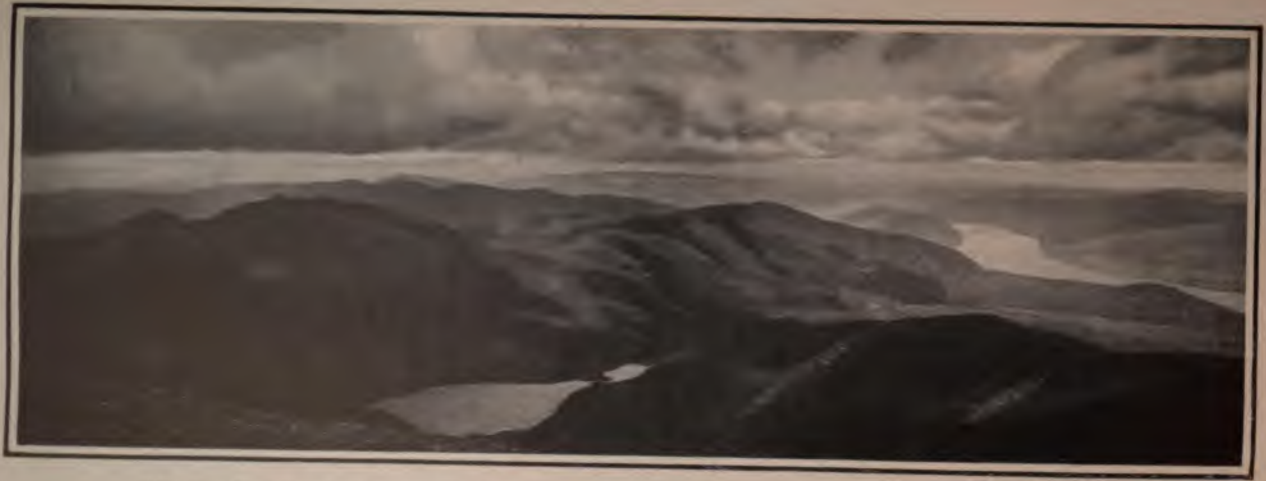


FIG. 40.—View from the Summit of Ben Lawers looking North-east along the great Axial line of Folding.

Photo. by W. LAMOND HOWIE, F.C.S.

anticlinals and synclinals become crushed together, and, as a consequence, the former horizontal extension of the beds becomes very much diminished; but what they lose in extent they gain in height, and as the beds gradually rise, a long and lofty ridge is formed, the major fold forming the crest of this great axial line of folding, and the minor harmonic folds forming the flanks.

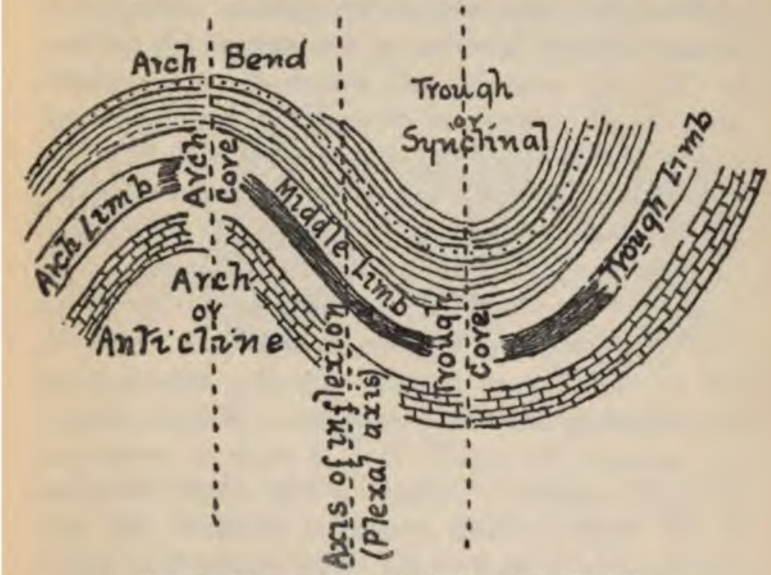


FIG. 41.—Diagram to show the different parts of a fold.

Towards the outskirts of such a great central ridge of folding, the strata would remain comparatively undisturbed, for here the outward and inward thrusts may be considered as equal, and so the resulting folds would be of a simple amphiplexal type. Proceeding towards the centre of such a great axial line in the folding, we find that while the inward thrust remains the same, the outward thrust has become more intense, owing to the gravity of the superincumbent mass. Consequently we have two unequal forces acting in opposite directions, the weaker one pressing inwards towards the central axis, the stronger pressing outwards away from the central axis. The result is that the axes of the folds no longer occupy a perpendicular position, but slope obliquely outwards, having been pushed over, as it were, by the stronger thrust, and in this way what is well known as the fan-shaped structure, or *structure en éventail*, has been produced.

The mechanism of the ridging up of such originally horizontal strata into a fan-shaped mountain structure, and the production of the different types of overfolding, has been developed in much detail by Professor Heim in his classic work, the *Mechanismus der Gebirgsbildung*. The simple type of fold has already been described, and we now pass to consider how the different types of overfolding have been produced. With an increasing pressure the middle limb is made to rotate and gradually assumes a position normal to the direction of the thrust. With continued pressure the arch rises and the trough sinks. The middle limb passes beyond the vertical, becoming inverted, so that the trough curve is brought below the arch curve and an overfold is produced. As a rule, we find in this simple type of the overfold, that the central parts of the fold have been squeezed thinner, while the main curves have been thickened. The proportional lengths of the limbs, however, generally remain the same. This type of overfold is shown in Fig. 42, *b*.

When, in the production of such an overfold, the middle limb is comparatively short, so that its decreased breadth is not sufficient to withstand the compressing force, a different structure is set up in the fold. In this case, the arch limb giving way in an upward direction and the trough limb in a downward direction, both of these limbs suffer from the horizontal thrust only. But the middle limb lying between the arch limb and trough limb is so wedged in between two masses, moving in opposite directions, that it suffers a rolling out or mangling process, and thereby becomes longer. (Fig. 42, *b* and *c*.)

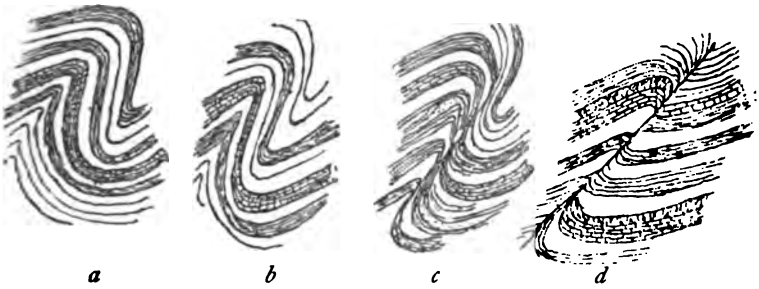


FIG. 42.—Diagram to illustrate overfolding, and the production of Reversed Faults.

As the strata, which constitute the fold, gradually give way under the increasing pressure, there will be a flow of the particles at the crest of the fold downwards towards the thinned middle limb. A similar movement takes place in the trough limb, the end of which is dragged upwards, being much thinned out at the middle limb.

On the convex or outside parts of the arch- and trough-curves there is a continual tendency of the particles to the constantly lengthening middle limb; on the concave or inside parts of these curves there is a corresponding movement from the centre of the middle limb towards the apices of the curves. The geologically *younger beds* of the folding system (*i.e.* the parts within the arch and trough axes) move *downwards below* the under side of the middle limb; the geologically *older beds* glide *upwards above* the upper side of the middle limb. These changes of position of the particles can never proceed, however, so quickly as the advancing movement of the overriding and under-thrust masses, for they have merely been rolled and dragged along by the latter. (See Fig. 42, *a* and *b*.)

Through the rolling out process described above, the mass of strata dragged over the arch bend grows thinner and thinner the greater its distance becomes from the overturning brow of the arch. In the same way, the lower portion of the middle limb, which feeds itself from the trough limb by dragging particles upwards, rolls out thinner and thinner the further it becomes removed from the trough bend. Between both these regions, the precise spot where the middle limb is at its weakest marks the special point where in the original formation of the inclined fold, the curve between arch and trough originally changed direction, and which has therefore experienced for the longest time the rolling and dragging-out action in both directions.

Whilst, in the first type of inclined fold described, an extent of strata corresponding with the width between the trough limb and the arch limb is predestined from the very beginning to be the later middle limb of the inclined fold; in the second type, the middle limb originates in great measure by the gradual curving round and rolling out of pieces of the two side limbs. During the infancy of the fold the particles eventually composing the middle limb were mostly portions of the lateral limbs, and underwent a mechanical transformation in their gradual transition into the middle limb. It is evident that the zones of strata which were thus dragged by the two side limbs into the central limb have, when combined, a collective breadth necessarily much inferior to that of the middle limb which has been *rolled out* of this material.

A third type of overfold may originate when the rolling out has gone so far that the middle limb becomes completely sheared out and a surface of dislocation takes its place (see Fig. 42, *d*), producing what is known as an overfault. We have thus availed ourselves largely of Professor Lapworth's *résumé* of the development of reflexed folds, as given by Heim in his great work. Professor Lapworth remarks that no one who has studied this subject can doubt the general correctness of Heim's views, and our apology, if such were needed for quoting so largely from Professor Lapworth's paper, is simply this, that we think, if these principles be applied to an explanation of the mountain structures seen in the Grampians, they afford, so far as we can judge, the most satisfactory and most complete explanation of them that has yet been advanced.[1]

In the succeeding part of this chapter we hope to be able to show that the strata of the different schist-zones, which have already been described, are generally arranged in a great series of inverted folds of the types just described. In these folds, as we have seen, both the limbs hade in the one direction. Sometimes the axes of these folds may be vertical, or they m make angles of any degree with the horizon. It will be evident that, by the repetition of such a series of isoclinal folds, a very thin bed may be made to spread over a great area, and present the appearance of a massive formation of great thickness. (See Fig. 43, *a* and *b*.)

---

[1] "Secret of the Highlands," *Geological Magazine*, vol. 1883.

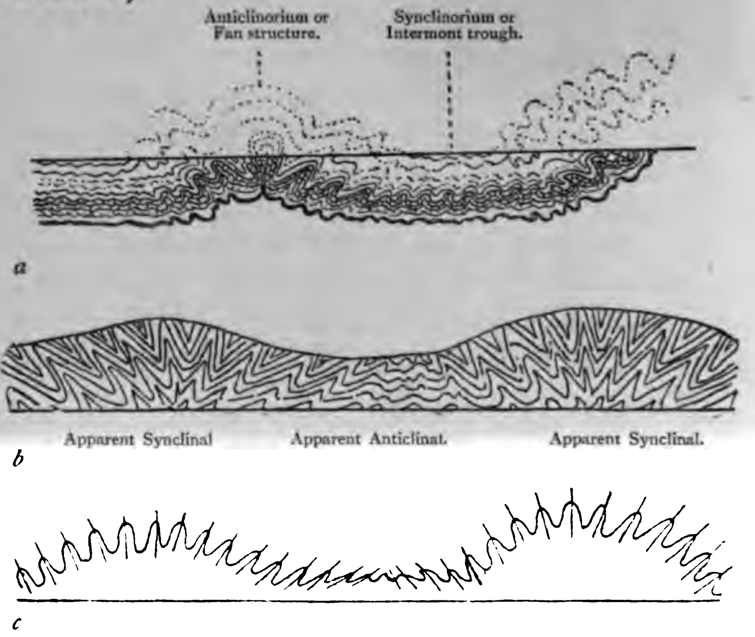

Anticlinorium or Fan structure.
Synclinorium or Intermont trough.
a
Apparent Synclinal
Apparent Anticlinal.
Apparent Synclinal.
b
c

FIG. 43.—Diagram to show the structure of highly-folded areas.

As we have already seen, these minor folds may often be combined in one great or major fold. When the axial planes are vertical in the centre and dip inwards towards one another on either side, they form the fan structure of Heim, the anticlinorium of Dana, and the endocline of Lapworth. When extensive denudation has removed the greater part of such a structure, the strata on each side will appear to dip towards one another in a simple synclinal arrangement, which would of course be entirely deceptive in this condition. Such a structure has been termed a pseudo-syncline. (Fig. 43, *a* and *b*.)

The complement of such a fan-shaped structure, or the region lying between two such structures, the synclinorium of Dana and the exocline of Lapworth, would present a series of isoclinal folds whose axial planes would be horizontal in the centre, but would dip away from one another on each side of the central axis. In highly denuded strata such an arrangement would appear as a simple anticline, which, like the former case, would be entirely deceptive; hence such an arrangement has been called a pseudo-anticline.

Abundant evidence of the effects of dynamic metamorphism can be seen in the schists of the Highlands, the extent to which the rocks have been altered being dependent upon their lithological character and the nature of the folding at the particular point where the bed is observed. It can be seen over and over again that the finer argillaceous strata have been more readily cleaved and folded than the more massive arenaceous beds. The folding of the beds is generally accompanied by a certain amount of shearing, and we find, as a rule, that the shearing appears to be more intense along the flanks of the great axes of folding than upon the crests. A consideration of the arrangement of the axes of folding will, we think, make this clear. In the centre of the main axis the folding is vertical, and as we proceed outwards from it the axes of the folds become less and less inclined, till they may eventually become almost horizontal. In the tightly-packed vertical folding which lies along the main axis shear-movements would be nigh impo sible, or could only be developed to a very limited extent. But as we proceed outwards from the central axis, and the axes of the folding get flatter and flatter, the shearing becomes more intense, and the original structure of the rock may be completely destroyed and a highly-developed schistosity superinduced upon the rock. In the Ben Lawers phyllites near the summit of Creag na Caillich, Killin, large cubes of iron pyrites, often measuring three inches long, occur. In many cases these crystals have been drawn out by shearing movements, Fig. 45 showing one of these crystals. Professor Bennett has kindly examined this crystal for us, and has made a quantitative estimate of the amount of shear to which it has been subjected. He says the distortion is almost a simple shear, its plane being nearly that of one plane of one pair of diagonals of the cube, and the amount of the shear approximately 0.08.

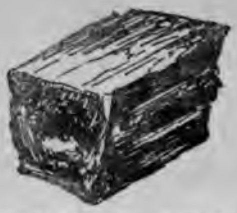


FIG. 45.—Deformed crystal of Pyrites, from the Ben Lawers Phyllite, Creag na Caillich, Killin.

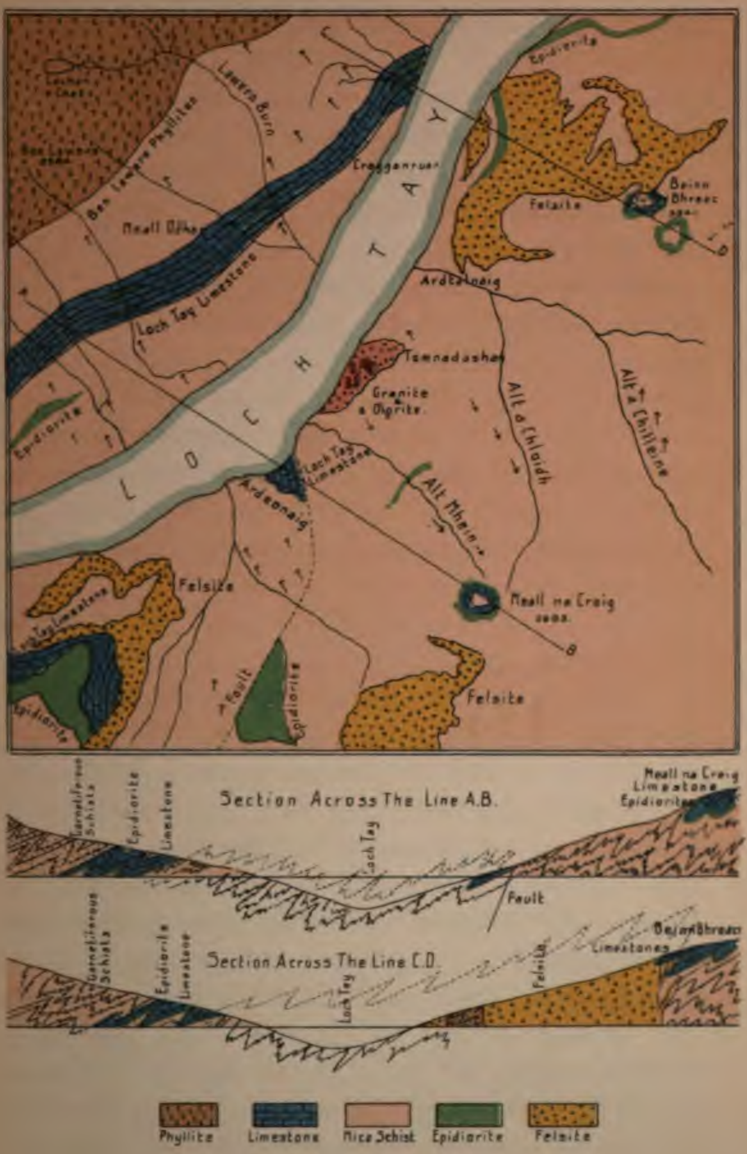
Turning now to an application of these principles to the structures seen in the Grampians, we may state at the outset that it is now a considerable number of years since we first examined the high ground lying between Loch Tay and Glen Lyon. (See Fig. 44.) In these early days we adopted the view, which is

even yet generally prevalent, that the schists composing this ridge were arranged in a simple synclinal structure, throwing off simple anticlines towards Glen Lyon and Loch Tay. Within recent years, however, it has gradually been forced upon us that we are dealing, not with a simple trough in a great series of symmetrical folds, but that we have here the backbone or core of the great geanticlinal along which the crystalline schists of the Highlands were first piled. Little now remains of the superstructure of this central core; it has been razed to its very foundations. Still, it seems to us that the structure of the schists, as seen in the Ben Lawers ridge, undoubtedly points to this having been the position of the main axis of upheaval of the mountain chain.

Further west, the position of this great backbone of schists may be traced through the ridge which separates Glen Lochay and Glen Dochart, and into the district of Loch Awe, where it can be recognized between Loch Fyne and the Sound of Jura. In this area, the beds which constitute the central ridge, or *Fächer*, belong to a horizon higher than those seen in the Loch Tay district. (See Fig. 44.) On the shores of Loch Fyne and the Sound of Jura the schists of the Upper Argillaceous Zone dip respectively north-west and south-east. In the area between, the quartzites of the Upper Arenaceous Zone are arranged in a shallow fan-shaped structure. In crossing this area from Loch Fyne to the Sound of Jura, the quartzites are found to succeed the Ardrishaig phyllite. Dipping towards the north-west the axes of the folds become gradually steeper and steeper, till they reach a line parallel to the main axis of Loch Awe, where they become vertical. From this point, and towards the Sound of Jura, the dip of the axes of the folds is now to the south-east, at a gradually lessening angle, till they reach the Sound of Jura. (See Sketch Map and Fig. 44.)

It seems to us that no better ground could be found for the study of this highly-interesting structure than the ridge north of Loch Tay. We now propose to describe several sections, passing from the north side of that ridge right across the frontier Highlands to the great boundary fault, for the purpose of elucidating this important structure.

By reference to the accompanying sketch map of the Southern Grampians, it will be found that, in the region to the north of Loch Tay, and between it and Glen Lyon, the schist zones occur in the following order: First, the Loch Tay Limestone; then the Garnetiferous Schist Zone; and, lastly, the Upper Argillaceous Zone. Further north, the Garnetiferous Schist Zone again appears, followed by the Loch Tay Limestone Zone. All along the northern side of Loch Tay magnificent sections are exposed in the beds of the streams which descend the sides of Creag na Caillich, Coire Fionn Lairig, Meall nan Tarmachan, Beinn Ghlas, and Ben Lawers. Everywhere the same general dip towards the north-west holds good, there being an apparent upward succession through limestones, garnetiferous schists, phyllites, and quartzites to the summit of the ridge. Now, as the dips are often considerable, say at an average of 45° near the level of Loch Tay, and increasing towards the summit of the ridge till they become vertical, this would give an enormous thickness of schists, probably



SKETCH MAP AND SECTIONS SHOWING THE STRUCTURE OF THE LOCH TAY DISTRICT.

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND

thousands of feet, and certainly far too much to be granted without careful examination, and at least some evidence to justify it.

Numerous fine sections of the Loch Tay Limestone, with its accompanying sills of epidiorite, are exposed along the base of the Ben Lawers ridge from Finlarig, near Killin, to Cragganruar, where it enters the Loch, and where it has been cut off by the great fault, which here crosses the loch (see Sketch Map). One can hardly examine any considerable section in the Loch Tay Limestone without being struck by the evidence which it gives of having undergone extensive folding, none of the other schists being so conspicuously folded as the limestone. One can, in fact, scarcely examine the limestone at any point without noticing this. Thus the section already referred to, as seen by the roadside at Druim na Lairig, shows very clearly the manner in which it has been folded. Perhaps the finest example seen in this district, of the extreme folding to which the limestone has been subjected, is that on the south side of Loch Earn, below the falls at Edinample. At this point the Loch Tay Limestone abuts against the Glen Ample fault at a low angle, and is seen to be plicated into innumerable folds. Besides these smaller folds, one can scarcely examine what appears to be a comparatively unfolded bed without having suspicions aroused that the simplicity is more apparent than real. For instance, we cannot examine any considerable section of the Loch Tay Limestone without noticing the presence of cores, round which the limestone has evidently been folded. From this, then, it would appear that the limestone, besides being plicated into comparatively deep isoclinal folds, has also had the limbs of these folds bent into minor harmonic folds, which obey the same law of overfolding and thinning as the major folds (see Fig. 46 and 47). The thickness of the Loch Tay Limestone in this district has been estimated at about 30 feet, and as the outcrop must be at least half a mile wide in many cases on a steep hillside, and with an apparent dip of about 45°, it will be seen that this necessitates a considerable folding of the bed to account for its apparent thickness (see Fig. 44).

In the recently-published geological map of the district, sheet 46, an outcrop of limestone is given as occurring in the bed of the Allt Tir Artair, and north-west of Meall Liath. It also appears near the 1600 feet contour line in the stream which descends Creag na Caillich. The outcrop of this limestone is thus well within the garnetiferous schists. We have not seen this outcrop, and cannot say whether it may simply be the Loch Tay Limestone brought in again by folding, or whether it represents a bed higher in the series. The upper boundary line of the Loch Tay Limestone can be pretty accurately traced, and, as a rule, there are no exposures to be found above a definite line. From this, one would assume that the folding of the limestone has been pretty equable over large areas.

Succeeding the Loch Tay Limestone, and evidently lying above it, we have the Garnetiferous Schist Zone; but here the ground is even more difficult, as these schists do not present to the eye the same amount of folding as is seen in the limestone. The reason of this may simply be, that there is not the same

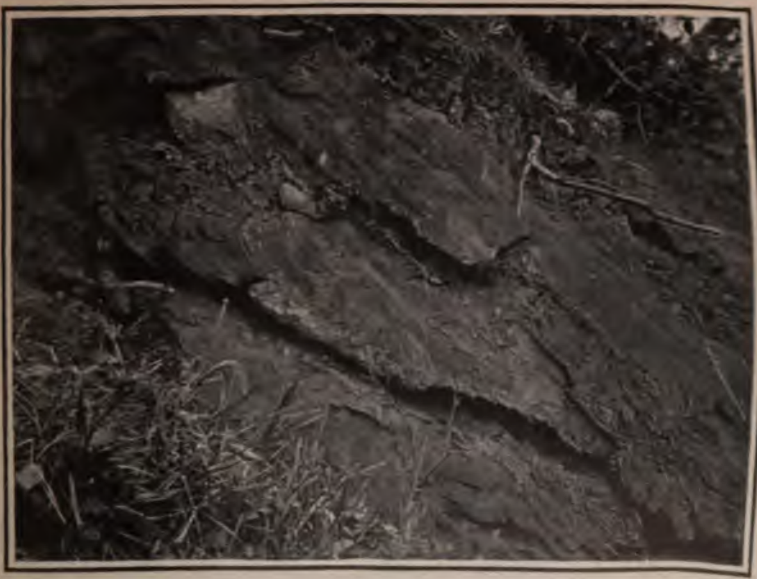


FIG. 46.—Outcrop of Folded Loch Tay Limestone, showing direction of over-folding. Druim-na-Lairig, Killin.

Photo. by P. MACNAIR.

amount of minor folding in the limbs of the isoclines as appears in the limestones. After having ascended the hillside for some distance, the limestones disappear and the garnetiferous mica-schists come on. Like the limestones beneath, they have the same steady north-west dip. No data seem available for the differentiation of these schists into separate well-marked beds. When the upper limit of the limestone is crossed, no definite horizon can be found till the phyllites of the Upper Argillaceous Zone are reached. Now, the question again arises as to whether we have here a continuous succession of schists, representing a great thickness of rock, or whether, on the other hand, the beds have been repeatedly folded upon one another. We are afraid we have not yet got sufficient data to solve this problem, but the latter view seems to be the more likely one. Above the garnetiferous schists, and lying conformably upon them, come the phyllites, thin schistose quartzites, and greywackes of the Upper Argillaceous Zone. This group gives evidence of intense folding, the character of the folding being well seen in many of the bare escarpments which occur along the summits of the ridge from Creag na Caillich to Ben Lawers, and in which the schists are clearly seen to be plicated into a series of isoclinal folds, with their axes hading towards the north-west. Proceeding down the other side of the ridge towards Glen Lyon, the schist zones are found to outcrop in exactly the same relative order; but the axes of the folds dip in the reverse direction, namely, to the south-east instead of the north-west (Fig. 44).

In the first place, let us describe a horizontal section taken along the line *CD* (see Fig. 44) in the coloured sketch map, beginning at Glen Lyon and passing through Creag na Caillich, the western end of Loch Tay, and Eildreach between Loch Tay and Loch Earn, thence crossing the head of Loch Earn and passing through Stuc a' Chroin, to the boundary fault on the Keltie Water.

From an inspection of this section it will be seen that the rocks forming the ridge to the north of Loch Tay have been plicated into a fan-shaped structure, in which the folds on the south side of the ridge have their axes hading towards the north-west, while those on the north side hade towards the south-east, those in the centre being in a vertical position. From this, one would infer that we have here a great axis of plication, from which the pushing forces have extended themselves outwards in a north-westerly and south-easterly direction. We may now trace the section towards the south-east, as far as the great boundary fault, and note the general effect of the plicating forces in that direction. Near the summit of the ridge, as we have already observed, the schistose phyllites and quartzites are seen to be plicated into a series of isoclinal folds, whose axes are in a vertical position. Proceeding down the hill, and towards the south-east, the axes of the folds become less and less highly inclined towards the north-west. When about half-way down, the Garnetiferous Schist Zone comes out from beneath the Upper Argillaceous Zone, the beds being folded in a similar manner, and with the axes of the folds dipping towards the north-west at an angle of about 45°. From beneath the garnetiferous schists, and near the

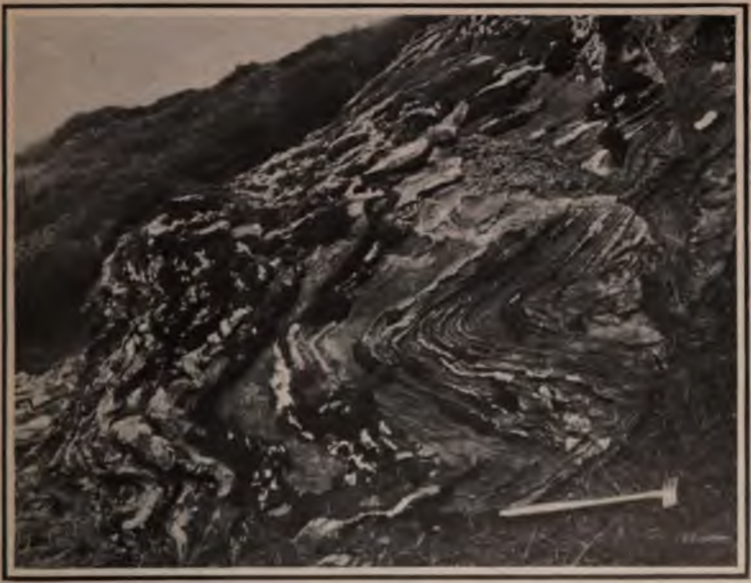


FIG. 47.—Outcrop of Folded Loch Tay Limestone. Head of Glen Ogle.

Photo, by J. W. REOCH.

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS

foot of the mountain, comes the Loch Tay Limestone, in which the character of the folding is more clearly seen.

From below the limestone there outcrops a group of flaggy schists, well exposed in the bed of the Dochart at the falls, and in the lower reaches of the Allt nan Sliabh behind Auchmore. They probably belong to a horizon lower than the limestone, and occupy the whole of the bed of the Allt nan Sliabh from its junction with the loch up to near the 1000 feet contour line. Unlike the schists lying immediately above the limestone, they contain few garnets, or are almost destitute of them. In the lower reaches of the Allt nan Sliabh they dip north-west, and probably continue across the loch. Traced up the stream the dip gradually lessens, till the schists become quite flat. About half a mile above the junction of the Allt nan Sliabh and the Allt an t-Socaich the Loch Tay Limestone again comes on. We have drawn it as conformably overlying the schists just described, and as underlying the garnetiferous schists which form the main bulk of Ben Leathan and Eildreach at higher levels.

The garnetiferous schists have also been drawn as plicated into a series of isoclinal folds with axes in an almost horizontal position. When we first examined this ground we considered that we had here a great thickness of schists; but, for reasons already given, we have also shown this part of the section as having been extensively folded. Some very instructive sections may also be seen in Glen Ogle, where the limbs of the isoclinal folds are themselves occasionally folded. At Dalveich, on the northern shore of Loch Earn, the Loch Tay Limestone comes out from beneath schists accompanied by the epidiorite. On the other side of Loch Earn the limestone again appears at the foot of Glen Ample, dipping at a low angle to the south-east, and abutting against the great fault, which, passing down Glen Ample, crosses Loch Earn at this point. On the east side of this fault we pass on to the Ben Ledi grits of the Lower Arenaceous Zone, which form the main mass of Stuc a' Chroin and Ben Vorlich. They have been plicated into isoclinal folds with the axes generally dipping towards the north-west. Near the summit of Stuc a' Chroin, and in the bed of the Allt a' Choire Fhuadaraich, an outlier of the "green beds" is seen folded in with the Ben Ledi grits. The main outcrop of the "green beds" in this section has evidently been cut out by the powerful fault already referred to. From Stuc a' Chroin the section passes to the east of Meall na Caora, and crosses the Ben Ledi grits, the axes falling gradually, then rising, as we approach the Highland border. From beneath the Ben Ledi grits emerge the slates of the Lower Argillaceous Zone, which are succeeded to the south by a series of grits. These in their turn appear to pass into the black shales and limestones of supposed Arenig age. Near Luirgeann the great boundary fault throws down the basal conglomerates and their interbedded lava into a vertical position.

The next section which we describe is taken about six miles to the east of that already given (see Fig. 44). It passes from Glen Lyon across Ben Lawers, Loch Tay, Meall na Creige, and Ben Chonzie, thence down Glen Turret to the boundary fault at Crieff. In the bed of the Allt Gleann Dathaig, north of Lochan na Lairige, exposures may be seen of the Loch Tay Limestone and

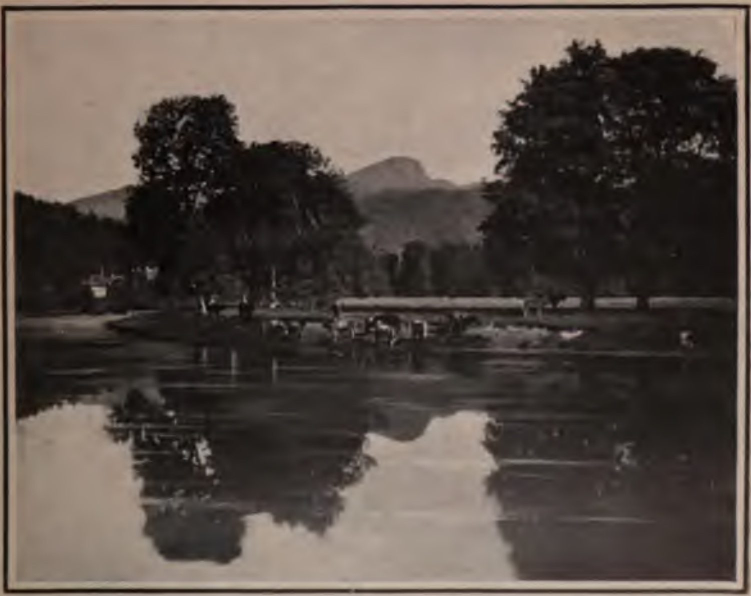


FIG. 48.—Creag na Caillich, Killin, from the Lochay.

Photo. by W. LAMOND HOWIE, F.C.S.

its accompanying epidiorites, with the axes of the folds hading towards the south-east. Ascending Ben Lawers by the east side of Meall Corranaich, above the limestones there come in garnetiferous schists, and then the phyllites and schistose quartzites, all dipping towards the south-east. At a higher level, a group of black shales and grits may be seen in the stream section, which evidently occupy a horizon higher than the phyllites. As we have already observed, they are not exposed on the summits further to the west, being preserved on the north side of Ben Lawers owing to the folding being deeper at this point. On the summit of Ben Lawers the phyllites and quartzites may be seen in an almost vertical position. As we descend the south side of the mountain, the hade of the axes of the isoclinal folds becomes reversed, being now towards the north-west. Numerous fine sections, showing the garnetiferous schists, the Loch Tay Limestone, the epidiorites, and also the schists apparently underlying the limestone, are to be seen in the Lawers Burn, the Allt an Tuim Bhric, and other streams descending the south side of the Ben. Crossing Loch Tay, the limestone is again exposed at Margmore, where it abuts against the Glen Ample and Glen Beich fault, which enters the loch at this point. Ascending the Allt Mheine, we cross a series of flaggy schists which evidently belong to a horizon lower than the Loch Tay Limestone, as at the top of the stream and on the summit of Meall na Creige an outlier of the limestone is found capping that mountain. The structural identity of the northern part of this section with that of Creag na Caillich is evident. That part of it lying to the south of Loch Tay, and to the east of the great fault, presents a somewhat different character from that of Ben Leathan and Eildreach, this being caused by the fault having a considerable down-throw to the west, which brings in the lower schists on the east against the Loch Tay Limestone and garnetiferous schists on the west. In the meantime, we class all the schists that appear to be below the Loch Tay Limestone as belonging to our Lower Arenaceous Zone. To what extent these flaggy schists are the equivalents of the grits and greywackes, which further to the south retain their original clastic structures comparatively unaltered, we cannot at present say. It is just possible that the grits and greywackes of Ben Ledi and Ben Vorlich may originally have passed northwards into finer sediments, while the increasing metamorphism in that direction would also tend to destroy the original clastic structures.

As we pass down the south side of Meall na Creige the same schists appear to come out from beneath the limestone, the dip of the axes of the isoclinal folds being somewhat irregular, but appearing on the whole to be towards the north-west. Crossing the summit of Ben Chonzie we recognize a gradually decreasing metamorphism, till the rocks of the Lower Argillaceous Zone appear in a comparatively unaltered condition. In Glen Turret the dip of the folds is seen to be steadily towards the north-west, at gradually increasing angles as we proceed south. About two miles to the south of Loch Turret the slates of the Lower Argillaceous Zone come from beneath the grits and greywackes. The slates are, however, soon covered by an outlier of the Lower Old Red Sandstone, resting unconformably upon the crystalline schists of the

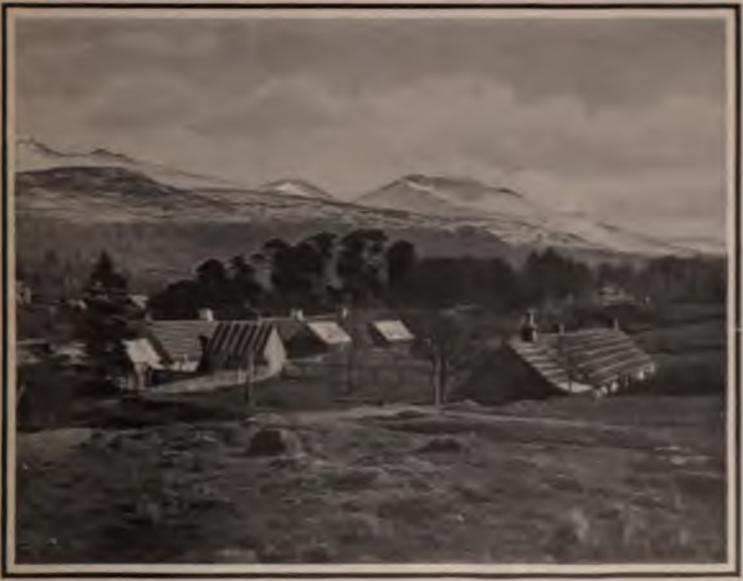


FIG. 49.—View of Ben Lawers and Ben Ghlas, from Killin.

Photo. by J. W. REOCH.

Highlands. To the south of Hosh the conglomerates have been thrown down by the great fault at high angles.

Farther east, in the valley of the Garry and the Tay, an almost similar section might be described. To the north of Blair Atholl the quartzites of the Upper Arenaceous Zone and Moine schists occupy the whole of the bed of the Garry from Dalnacardoch to near Blair Atholl. The dip of the axes of the isoclinal folds is towards the south-east at considerable angles. About two miles north of Blair Atholl the great fault, so often alluded to, passes north-eastwards towards the head of Glen Tilt. On the east side of this fault we pass on to the Glen Tilt Limestone and black schists of the Upper Argillaceous Zone, which are here repeated in isoclinal folds, whose axes are almost vertical. These are well exposed in the Banvie, below the line of fault. Proceeding down the Pass of Killiecrankie we cross the quartzites, and, near the foot of the Pass, the black schists and phyllites. The axes of the folds now dip towards the north-west. South of Pitlochry the Garnetiferous Schist Zone is followed by the Loch Tay Limestone Zone, the Lower Arenaceous Zone, and finally, near the boundary fault at Birnam, the Lower Argillaceous Zone. This section presents much the same features as those which we have already described. Across the frontier Highlands the axes of the isoclinal folds dip towards the north-west at angles which gradually increase till we reach the boundary fault. An increasing metamorphism can also be seen as we trace the schists northward from the boundary fault towards the great axial line of folding.

Still farther east, in Glen Shee, a similar structure and succession can be made out. At the Spital of Glen Shee the black schists have been thrown into a series of vertical isoclinal folds. Proceeding down the glen we pass successively over the phyllites and garnetiferous schists, and to the south of Blacklunans the Loch Tay Limestone, with its accompanying epidiorites. At Craigton we reach the main outcrop of the "green beds," which is repeated in outliers further to the south at Blackhall. From this point to the Bridge of Cally the grits of the Lower Arenaceous Zone are repeated in isoclinal folds, with axes hading towards the north-west, and gradually becoming steeper and steeper as we approach the boundary fault, till eventually, at the Bridge of Cally, the slates of the Lower Argillaceous Zone emerge from beneath the overlying grits. It will be unnecessary for us to follow these different schist zones into the Highlands of Kincardineshire, Aberdeenshire, or Banffshire. Besides, we have not had an opportunity of examining any part of the area in detail. Notwithstanding the fact that the schist zones of the area have been much invaded by later intrusions of granite, we can still make out the same succession and structural arrangement of the schists as we have already seen to exist further to the west. We think that there cannot be any doubt that this great axial line of folding, ushering in lower and lower schist zones towards the Highland frontier, is prolonged north-eastwards to the Banffshire coast.

We now return to examine several sections to the west of that first given (see Fig. 44). The first we take passes from Glen Lyon across Meall Ghaordie to Corrycharmaig in Glen Lochay, and thence across

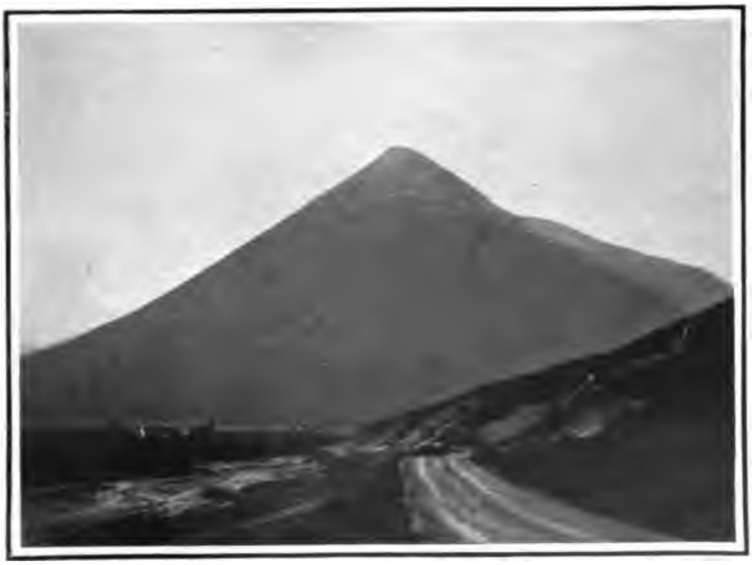


FIG. 50.—Ben Doriean, from the South.

Photo. by J. W. REOCH.

Creag Mhor, on the dividing ridge between Glen Lochay and Glen Dochart. From this point the line of section runs across Glen Dochart at Ardchyle and over the summit of Creag Mac Ranaich to Balquhidder; crossing the Balvaig it cuts across the summits of Beinn an t-Shithein, Ben Vane, and Ben Ledi, terminating at the boundary fault on the shores of Loch Venachar. Several fine sections of the Loch Tay Limestone are exposed in the Allt Laoisich, near Stronuich, in Glen Lyon, the axes of the folds dipping towards the south-east. Ascending this stream to the summit of Meall Ghaordie, we pass over the garnetiferous schists on to an outlier of the phyllites, which caps the summit of the latter mountain. Proceeding down the south side of Meall Ghaordie we again pass on to the garnetiferous schists, which dip towards the south-east; at Tullich the Loch Tay Limestone is again exposed, also dipping towards the south-east. After crossing the River Lochay at Corrycharmaig, the garnetiferous schists are again seen to pass below the phyllites of Creag Mhor, to the east of which passes one of the powerful N.N.E. and S.S.W. faults. The effect of this fault has been to shift the beds on the west side further south, thus bringing the Loch Tay Limestone against the phyllites. As these faults are later than the plication of the schists they must tend to break up and destroy the original tectonic arrangement of the schists. In this case beds which were originally on the north side of the great axial line of folding have been brought into line with those on the south side. Crossing Creag Mhor, we again meet with the garnetiferous schists coming out from beneath the phyllites, but the axes of the folds now dip towards the north-west. Descending to the level of the Dochart, we find the Loch Tay Limestone coming out from beneath the garnetiferous schists of Creag Mhor, from which point they can be traced up the stream to the south of Ardchyle (Glen Dubh). In ascending the stream the limestones get flatter and flatter, till they eventually roll over, and the garnetiferous schists again come in. These can be traced up Glen Dubh to the summit of Creag Mac Ranaich and Cam Chreag, where they appear to be about horizontal. Tracing the garnetiferous schists southwards towards Balquhidder, they are found to dip towards the north-west at a low angle, and the Loch Tay Limestone crops out on the eastern side of the Kirkton Glen. From this point the section crosses the Balvaig to the top of Beinn an t-Shithein, and the schists belong to the Lower Arenaceous Zone. Near the summit of the latter mountain there is an outcrop of epidiorite, which makes a prominent feature from Strathyre. The section now crosses Ben Vane, near the summit of which outliers of the Loch Tay Limestone have been faulted down into the grits of the Lower Arenaceous Zone. On crossing to Ben Ledi an outlier of the "green beds," stretching from the head of Stank Glen to the shores of Loch Lubnaig, has been detected by the officers of the Survey (see Fig. 51). In this part of the section the dip of the axes of the isoclinal folds is fairly steady towards the north-west, and, like those already described, rises towards the vertical as we approach the Highland frontier. We now come to the great mountain of Ben Ledi on the west side of Loch Lubnaig, in which numerous interesting sections are to be seen, illustrating both the petrological character and structural features of the grits and greywackes which constitute our Lower Arenaceous Zone. Ben Ledi consists almost entirely of these grits and greywackes, which have been piled up into isoclinal folds, whose axes dip towards the north-west at an average angle of 50°. When dealing with the question of the thickness of these rocks we said that no reliable data had yet been obtained regarding this important point, and till that was done it would be impossible to speak definitely as regards the amount of folding that has taken place in such a mountain mass as Ben Ledi. In the meantime it seems highly probable that the beds are of no great thickness, and that such mountain masses as Ben Ledi, Ben Vorlich, and Ben Venue (see Figs. 51 and 52), have been formed out of comparatively thin beds, which have been folded and re-folded upon one another. On the south side of Ben Ledi the slates of the Lower Argillaceous Zone emerge from beneath the grits, and a narrow strip of black shales belonging to the supposed Arenig group lies immediately against the great boundary fault, which crosses Loch Venachar near Milton.

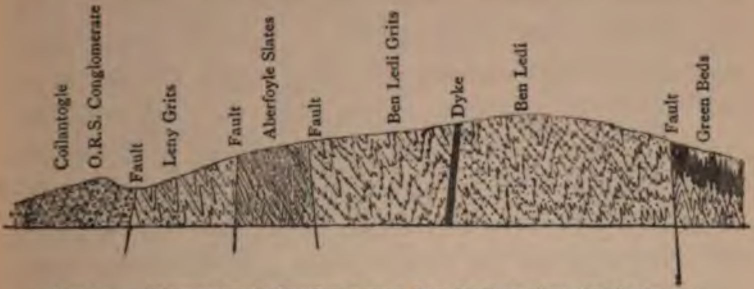


FIG. 51.—Diagrammatic Section across Ben Ledi to show its Geological Structure.

The next section which we describe (see Fig. 44) is taken about twelve miles further to the west, and runs from the north of Tyndrum across the high ground between Strath Fillan and Glen Falloch, whence it passes along the eastern side of Loch Lomond, over the summit of Ben Lomond, and southwards to the boundary fault at Balmaha. At Tyndrum one of the great N.N.E. and S.S.W. faults occurs, which has on its western side a group of massive quartzites with lenticular beds of mica-schist, belonging to our Upper Arenaceous Zone, and containing schists of the Moine type. The dip of the axes of the folds is towards the south-east. Excellent sections of these rocks can be seen in the higher reaches of the Allt nan Sal and the River Fillan. The schists on the east side of the great fault belong to the Upper Argillaceous Zone, and consist of the phyllites and thin-bedded quartzites, which are so characteristic of that zone. Like those of the massive quartzites, the axes of the isoclinal folds hade towards the south-east. On crossing the high ground between the Coninish Water and Glen Falloch, by the Allt Gleann Achrioch, the phyllites are seen to merge into the garnetiferous schists, which are followed by outcrops of the Loch Tay Limestone. These continue over the ridge to the Allt Fionn Ghlinne, where the main outcrop of the "green beds" comes from beneath the garnetiferous schists. At this point another of the great N.N.E. and S.S.W. faults occurs. Crossing Glen Falloch, we find the line of section runs along the eastern side of Loch Lomond to the summit of Ben Lomond, and passes across a group of schists belonging to the Lower Arenaceous Zone. There is, however, a remarkable difference both in the structural aspect of this section, and the extent to which the rocks have been metamorphosed, when compared with the sections already described further to the east. We no longer find the schists thrown off from the great axial line of folding in a series of isoclines whose axes dip steadily towards the north-west; nor do we find the foliation planes running in comparatively unfolded lines parallel to the axes of these folds. Over the whole of this area the grits become more completely granulitized, passing into mica-schists, and the foliation planes are also seen to be corrugated to a considerable extent. We shall presently see that this structural difference and increasing metamorphism, as we proceed from the eastern to the western end of the Grampians, has probably been caused by an increase of the lateral pressure from the south-east. The effect of this would be to push over the isoclinal folds towards the north, and develop another fan-shaped structure to the south of the present line of the boundary fault. It is also most likely that an area of maximum crushing and

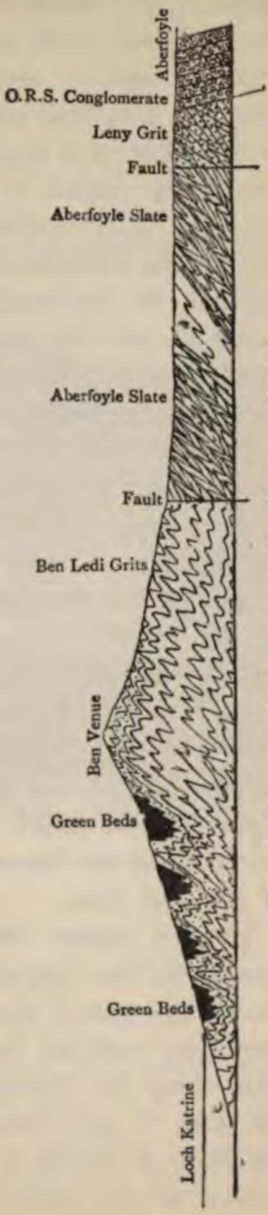


FIG. 52.—Diagrammatic Section across Ben Venue to Aberfoyle.

metamorphism would exist along a line midway between the two great axial lines of folding. Structurally the rocks in such an area would appear to be arranged along an anticlinal axis, though really they would be in the form of a synclinal double fold. So far as we have been enabled to understand it, this seems to be the most likely explanation of the structure of that part of the Grampians now being discussed; and the anticline in the bedding, according to the views of Jamieson and the earlier geologists, as well as the anticline of foliation of the Geological Survey, appears to be entirely deceptive.

The part of this section which lies between the head of Loch Lomond and the summit of Ben Lomond seems to be situated upon this line of intense crushing and metamorphism, and it is difficult to tell in what direction the folds are dipping. To the south of Ben Lomond, on Sron Aonaich, an outlier of the "green beds" has been preserved by being let down between two faults. Still further to the south, the Ben Ledi grits again come to the surface, followed by the slates of the Lower Argillaceous Zone, which appear to the south of Sallochy wood. These are succeeded at the boundary fault at Balmaha by bands of grit and slate.

The last section which we describe is taken across Cowal, for the purpose of showing the structure of the western part of the area under notice (see Fig. 44). Beginning near the head of Loch Awe, it runs down Glen Aray to Inveraray on Loch Fyne. Crossing the loch, it runs from Strachur down Loch Eck to the Firth of Clyde at Dunoon. In that part of the section to the north of Loch Fyne the grits and

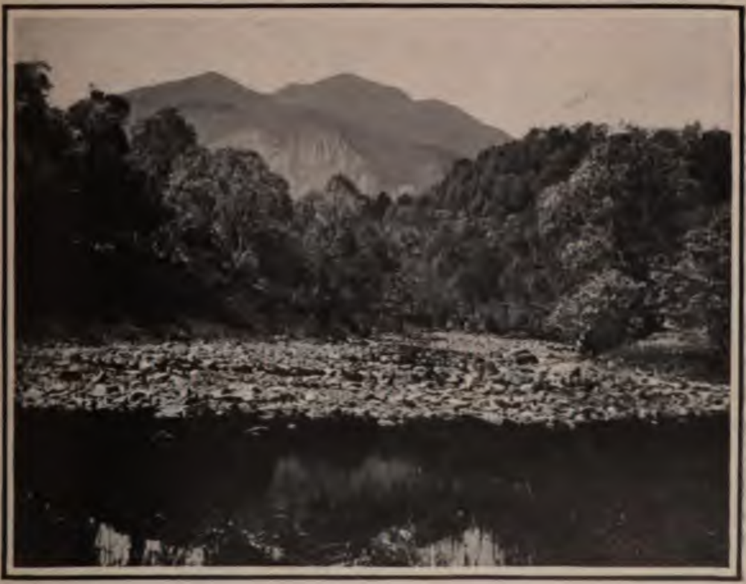


FIG. 53.—Ben Venue, from the Trossachs.

Photo. by J. W. REOCH.

quartzites of the Upper Arenaceous Zone, and the phyllites, black schists, and limestones of the Upper Argillaceous Zone, are arranged in a fan-shaped structure, as has already been pointed out. At Loch Craignish the phyllites and black schists of the Upper Argillaceous Zone have been thrown into a series of isoclinal folds, whose axes hade towards the south-east at an angle of about 30 degrees. Traced further east, towards the north end of Loch Awe, the schists of the Upper Argillaceous Zone pass below the volcanic rocks of the Lower Old Red Sandstone of Lorne, and are consequently hidden in that part of our section. Above the phyllites of the Upper Argillaceous Zone come the grits and quartzites of the Upper Arenaceous Zone, also dipping towards the south-east. On approaching the shores of Loch Awe the axes in the isoclinal folds of the grits and quartzites become vertical. From this point, and proceeding down Glen Aray, the axes of the isoclinal folds are reversed, being now to the north-west. The angle of dip of the axes gradually descends till, on approaching the shores of Loch Fyne, the grits and quartzites are replaced by the phyllites and limestones of the Upper Argillaceous Zone, and the dip reaches nearly the same angle as was observed at Loch Craignish, but is in an opposite direction. From this it will be seen that we have here exactly the same fan-shaped structure as was seen on the ridge north of Loch Tay, and we consider that we have here the western prolongation of the great axial line of folding, or backbone, of the Grampians, from which the crustal movements have pressed outward towards the north-west and south-east. On crossing Loch Fyne to

Strachur, it will be seen that the phyllites and thin quartzites of the Upper Argillaceous Zone are continued across the loch, and, still dipping towards the north-west, these are succeeded at the south by a narrow band of garnetiferous schists, and at Ballimore by the Loch Tay Limestone, with its accompanying altered basic rocks. To the south of this, and from beneath the Loch Tay Limestone, come the "green beds," followed by the underlying grits and greywackes of the Lower Arenaceous Zone, still having the axes of their folds dipping towards the north-west. As we approach a line running down the centre of Cowal, through the heads of Loch Goil, Loch Striven, and Loch Riddon, and the hills to the north-west of Tighnabruaich, we find the axes of the isoclinal folds approaching the vertical, as well as an accompanying increase in the amount of metamorphism. We are here on the centre of our synclinal double fold, or pseudo-anticline of Lapworth, the supposed anticline of bedding, according to Jamieson and the geologists of the latter half of last century, and the anticline of foliation of the officers of the Geological Survey. To the south of this central axis of folding the grits and greywackes are repeated in isoclinals, whose axes now hade towards the south-east. At Dunoon, on the Firth of Clyde, the phyllites of the Lower Argillaceous Zone emerge from beneath the overlying grits with a reversal of dip.

In the paragraph with which Professor Lapworth concludes his paper on "The Secret of the Highlands," we find him shrewdly suspecting that such valleys as those of the Great Glen and Loch Tay may not, after all, be anticlinal valleys, but are really depressed intermont synclinal troughs, though he does not appear, as we have already remarked, to have examined this ground in any detail. So closely has Professor Lapworth in this paragraph approached the general principles which we have advanced, that we do not hesitate in quoting it in its entirety. Thus he says: "In more easily convoluted regions, or in mountain chains of much higher antiquity, this inevitable relation of sunken trough to mountain area is necessarily less conspicuous

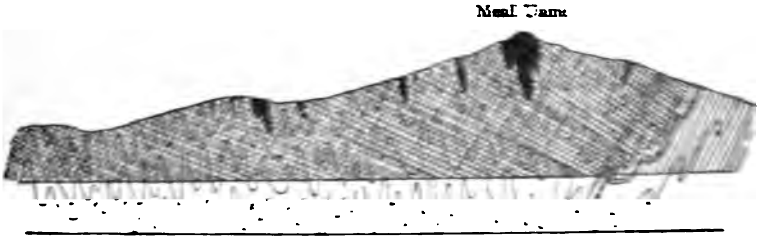


FIG. 54.—Section across Meal Uaine near Pitlochry

and long eludes detection owing to the bewildering complexities of the strata involved. But it is by no means impossible that the long straight (longitudinal or strike valleys) and so-called anticlinal valleys of the Scottish Highlands, such as those of the Great Glen and Loch Tay, walled in by steep hill-slopes and occupied by lakes of profound depth, are nothing more than greatly depressed intermont *synclinal troughs*, owing their origin to the same causes which bring about the slow secular elevation and approximation of their flanking ranges."[1]

A study of the great axial lines of folding which occur in the schists of the Highlands, shows that, during the processes of mountain building, the component strata were upheaved into a series of fan-shaped structures and intermont troughs (see Fig. 43). Little now remains of the superstructure of this early mountain chain, it having been reduced to a mere basal wreck of its former self by the long and continued action of subaerial and marine denudation. By carefully considering the fragments that are now left of this ancient chain, it appears that the great central massive must have risen over what is now the Midland Valley of Scotland.

---

[1] "The Secret of the Highlands," *Geological Magazine*, 1883, p. 344.

Along the shores of the Firth of Clyde a fragment of the northern limb of this central massive is still exposed. The axis of this fan-shaped structure must have coincided roughly with a line drawn through the Midland Valley in a north-east and south-west direction. From this axis the crystalline schists of the Highlands were thrown off in a complex series of isoclinal folds, the oldest strata being brought into the centre of the fan. As the ridging up of this structure proceeded, two great lines of weakness became developed along the northern and southern flanks of the massive, the position of these lines being still shown in the Highland and Southern Upland boundary faults. No doubt these faults would have been originally of the nature of thrust planes, which, during later geological times, settled down as normal faults, carrying down the crest of the massive and its overlying crust of younger rocks.

As we proceed northwards, another great massive appears to have been developed along the axis running from the Sound of Jura by Loch Awe, Ben Lawers, and Ben Vrackie, from which point it was continued into the eastern Highlands. This has been named the

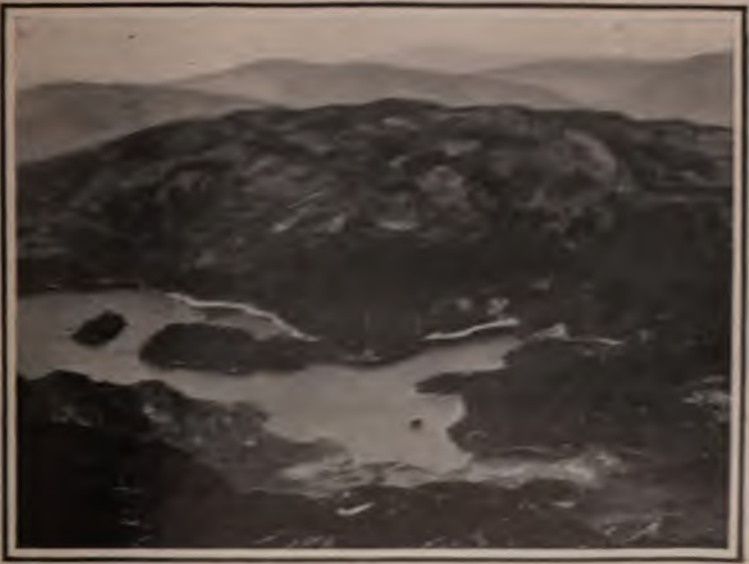


FIG. 55.—Loch Katrine, with Ellen's Isle and Ben A'an, from the summit of Ben Venue.

Photo. by J. W. Raince.

Ben Lawers *Fächer*. Between these two great axial lines of folding there was an intermont trough, from which the axes sloped away towards the north-west and south-east at gradually decreasing angles. The axis of this trough has been traced through Kintyre, and down the centre of Cowal. Bending round by Ben Lomond it appears to enter the boundary fault to the east of Ben Venue (see coloured sketch map at end).

It ought also to be noted that, in the ridging up of these structures, the forces seem to have been stronger, and to have exerted more power, towards the west than in the east of the mountain chain, the result of this being that in the west these great axes of folding have been driven much closer together, so that the axes of the minor folds are much steeper over larger areas, and the crumpling of the rocks more intense, in the west than in the east. This is clearly shown by a comparison of the section drawn across Ben Lawers to Comrie, with that drawn from Loch Awe to Dunoon. In a word, the great axial lines of folding appear to open out as they are traced from west to east.

Cross faults, of the nature of lateral wrenches, cut across the Highlands, and on the west side of these the strata have been driven successively towards the south. The Loch Tay fault, which has been described, is one of these, and others occur to the west of it. There cannot, we consider, be any doubt that these also are the result of the more intense compression towards the western end of the chain.

CHAPTER VII

THE ROCKS OF THE HIGHLAND BORDER, OR MARGINAL BELT

> The deep has power on the height,
>   And the height has power on the deep;
> They are raised for ever and ever,
>   And sink again into sleep.
>
> TENNYSON.

ALONG the Highland frontier, and immediately to the north-west of the great boundary fault, there occurs a remarkable group of rocks which the Geological Survey consider to be of Arenig age, and which are supposed to be identical with a similar group of rocks containing Arenig fossils found in the south of Scotland (see Figs. 58 and 62). The identification of the rocks seen along the Highland frontier with those of the Southern Uplands is, however, entirely dependent upon the similarity of their petrological characters, as no fossils have yet been found in the Highland rocks. Geographically, this narrow zone of rocks (for it is nowhere more than a mile in width) has been traced from the Island of Arran right across the Highland frontier into Kincardineshire. It does not appear as a continuous belt, as it is entirely awanting at certain places where the crystalline schists of the interior and

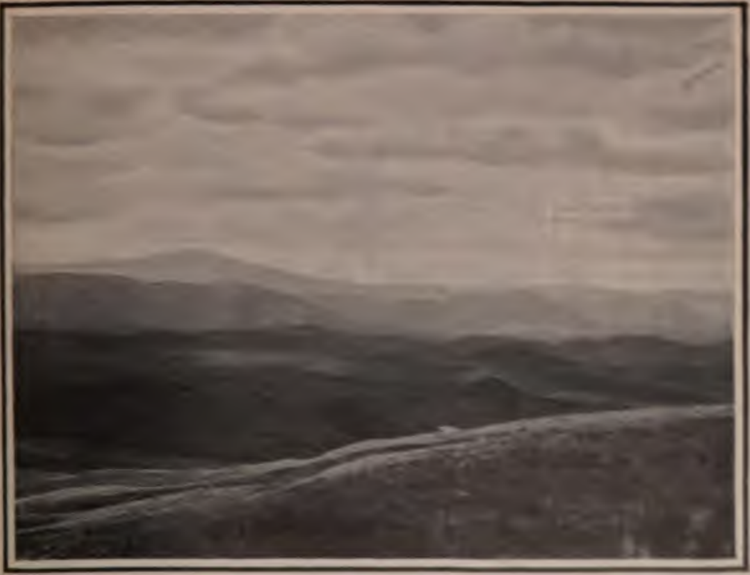


FIG. 56.—View along the Marginal Belt, with Ben Ledi in the distance.

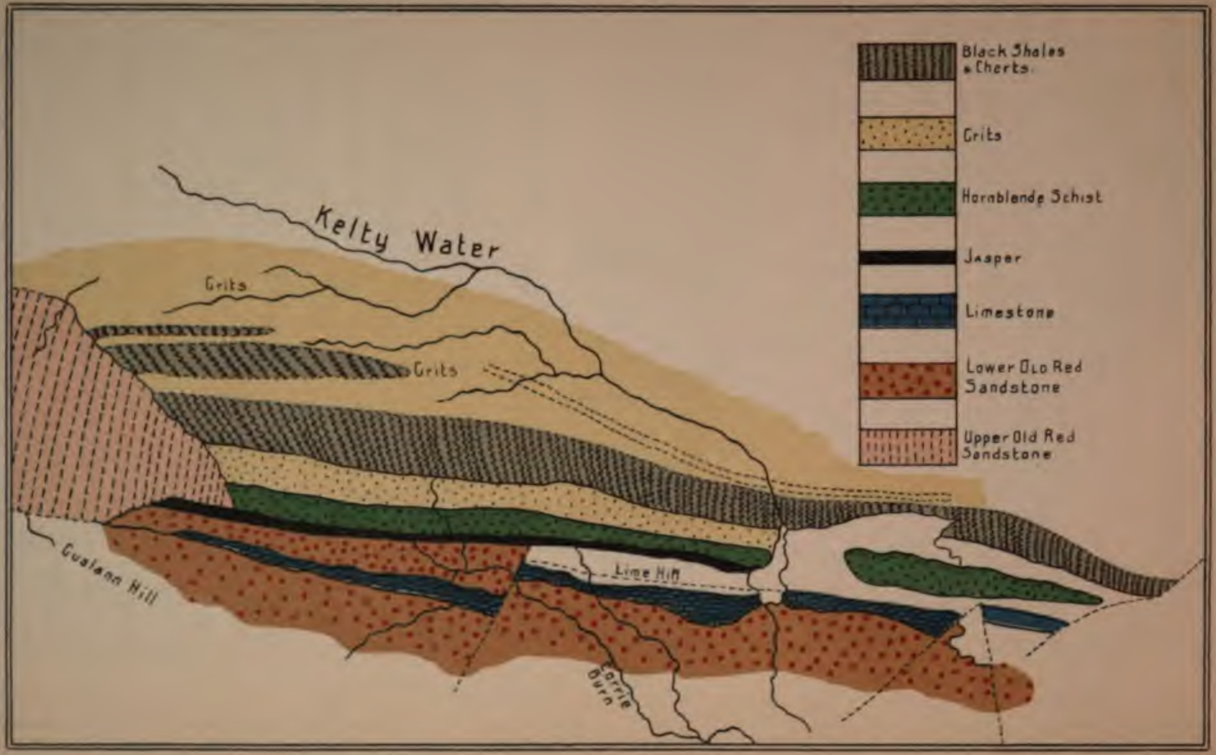
Photo. by S. FINGLAND.

the later Palaeozoic rocks abut against one another. It may thus be said to appear in lenticular strips at intervals, separated by the crystalline schists. Tracing these rocks from west to east, we find them exposed in North Glen Sannox in the Island of Arran. On the mainland no exposure has yet been found till we pass to the east side of Loch Lomond, whence a continuous belt has been traced from Gualann Hill—near which point they enter Perthshire—north-westwards by the Kelty Water, Clashmore, Arndrum, Aberfoyle, Loch Venachar, and the Pass of Leny. From this point we are not aware that these rocks have again been detected in Perthshire, but in passing into Forfarshire they are seen extending from Cortachy to about a mile beyond Clattering Bridge in Kincardineshire. They again appear to the north of Drumtochty Castle, whence they stretch to the Braes of Bervie.

In Glen Sannox this belt of supposed Arenig rocks consists of black shales or schists, associated with volcanic rocks, which are found to be interbedded with the afore-mentioned sediments, and some of which may be intrusive in them. The black shales have been folded to a considerable extent, and cleaved, and the cherts have also been folded and granulitized. The igneous rocks accompanying these sediments have suffered deformation, and may now be classed as epidiorites. A volcanic agglomerate has also been found in association with them. As a whole, these rocks of supposed Arenig age do not appear to be less altered than the schists of the ordinary Highland type which accompany them. In the Island of Arran this supposed Arenig belt is seen to be flanked on either side by schistose grits of the character already described as seen along the Highland frontier. They dip towards the east or east-south-east at high angles, thus giving the Arenig belt the appearance of being intercalated between, and forming an integral part of, the Highland series. As they all dip towards the south-east, the Arenig belt appears to overlie the schists of the interior. No reliance, however, can be placed upon this apparent order of succession, as we shall see that to the east of Loch Lomond it is reversed, the whole series apparently dipping beneath the schists of the interior. Nor has any evidence been found, in the Island of Arran, which would justify the separation of the supposed Arenig belt from the crystalline schists of the Highlands.

Crossing now to the belt exposed between Loch Lomond and the Pass of Leny in Perthshire, we find a somewhat similar series of rocks to that described as occurring in the Island of Arran. Emerging from beneath the Upper Old Red Sandstone outlier of Gualann Hill, they consist of black shales, cherts, and grits, with accompanying beds of altered basic rocks; the shales are occasionally graphitic, and are sometimes veined with quartz. The cherts are of a dark grey colour, and reddish flinty bands occur at places. They have been searched for fossils, but no undoubted organic remains have as yet been found in them.

Passing now to a more detailed description of this problematical belt as seen in Perthshire, we may note at the outset that no well-marked break has been found in this area, such as has been described by Mr. Barrow as occurring in Forfarshire. It forms a narrow zone, stretching from Kilmahog quarry to the west of Leny House, near Callander, where the outcrop is com-



Geological Sketch Map showing the Rocks of the Marginal Belt.

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS.

paratively narrow. Keeping to the north-west side of the boundary fault, it crosses Loch Venachar near Milton, the width of the outcrop being much the same. Upon reaching Aberfoyle the outcrop begins gradually to widen for a distance of five miles, till it plunges beneath the Upper Old Red Sandstone of Gualann Hill, where it reaches the maximum width of about half a mile. At this point some fine sections are exposed in the Corrie Burn and Kelty Water.

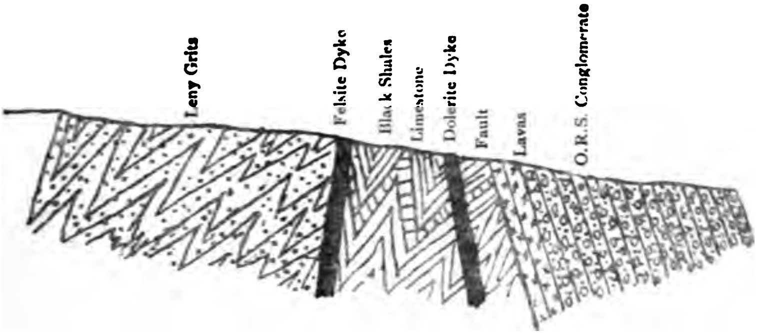


FIG. 57.—Diagrammatic Section across the Kilmahog Quarry, near Callander.

The section exposed in the Kilmahog quarry, on the hills to the east of the Pass of Leny, was long ago described by Professor Nicol. The excavations, which are of considerable depth, follow the outcrop of the strata across the hillside. The rocks seen in this section consist of greywackes, shales, and limestones, which are pierced by a dyke of felsite. The clastic rocks dip at a high angle to the north-west, the apparently lowest beds being the rusty greywackes, which are followed by black shales, limestones, and greyish and reddish shales (Fig. 57). As has already been observed, no reliance can, however, be placed upon the apparent order of succession. It is worthy of notice that Nicol was struck with the apparently unaltered condition of these rocks, and he remarks that, "both the texture and colour of the limestone, and the black carbonaceous-looking shales associated with it, remind us rather of the Carboniferous formation than of a Primary deposit." In our Historical Introduction we have already referred to the manner in which this section influenced Nicol's opinion, regarding the relationship between the frontier belt of slates and the schists of the interior.

From the shores of Loch Venachar south-westwards to Gualann Hill the Geological Survey map shows a series of grits lying to the north of the zone of black shales and cherts. We have not been able to differentiate these grits from the Leny series, and they appear to us to be an integral part of the Highland rocks. Petrologically the rocks are the same, and we can find no evidence of a thrust plane, either in the section exhibited in the Loch Katrine aqueduct, or on the surface.

Throughout the area, the black shales and cherts, which lie to the south of the grits just referred to, appear to dip at high angles towards the north-west, and thus apparently underlie the rocks of the Highlands. This zone consists of a thick series of cherts and shales, which alternate with one another. The shales have a dark carbonaceous or graphitic appearance, and are associated with splintery mudstones. They have also a strong resemblance to the graphitic shales of the Silurian rocks of the Southern Uplands. Specimens have been obtained by the Survey from the Leny quarries, which have been described by Professor Lapworth as shadows of grapholites. The cherts are usually of a light or dark grey colour and weather white upon

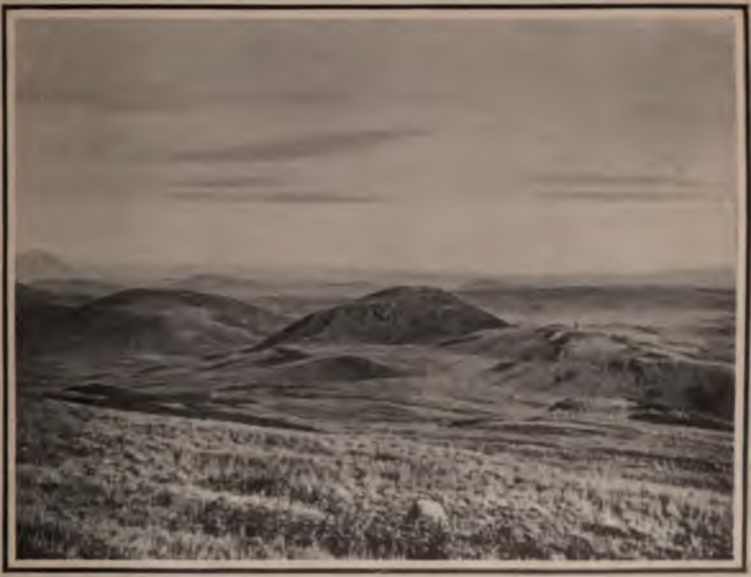


FIG. 58.—Lime Hill, on the Marginal Belt, near Aberfoyle.

Photo. by S. FINGLAND.

exposure, in which condition the fine banding showing the original stratification can be seen. Round or elliptical-shaped bodies resembling *radiolaria*, but without any evidence of spirals, occur in the cherts. The cherts are seldom of any great thickness, the individual beds ranging from one-half to two inches. As has already been pointed out, in Perthshire these blocks dip at high angles towards the north-west, but in the Island of Arran they dip towards the south-east, from which we infer that they have been folded along with the Highland schists. Many fine examples of the folding of the cherts and shales can be seen between the Corrie Burn and the Kelty Water, the folding being typically isoclinal (see Fig. 59). The axes of the folds, and pitch, vary considerably, and areas are found in which their strike stands almost at right angles to their dominant strike across the Highland frontier. In places the cherts have been considerably crushed and shattered, the fragments having been re-cemented with silica.

Where the black shales and cherts emerge from beneath the Upper Old Red Sandstone of Gualann Hill they exhibit three outcrops, the two most northerly of these being about half a mile, and a mile, in length respectively (see sketch map). The most southerly, which is the main outcrop, stretches almost continuously from Gualann Hill to Aberfoyle, and is intersected by numerous dip faults. Where the main outcrop crosses Corrie Burn it has a width of about 500 feet, but when traced eastward the width gradually diminishes, till N.E. of Aberfoyle it is not more than about 30 feet.

As to the manner in which the black shales and cherts are related to the grits which lie still further to the north, it would be difficult to speak with any degree of assurance. We have hitherto been unable to find any reason for separating them out from the Highland rocks: and we believe that the main outcrop comes out from below the grits; while the more northerly outcrops are inliers surrounded on all sides by the younger grits, with which they have been folded (see Figs. 59 and 60).

To the south-east of the outcrop of the black shales and cherts there occurs a band of grits, which comes out from beneath the Upper Old Red Sandstone of Gualann Hill, and which can be traced eastwards as far as Aberfoyle. The maximum width of the outcrop of this bed is about 500 feet, and it can be well seen in the bed of the Corrie Burn.

The grits belonging to this group can usually be distinguished from the Leny grits, which lie to the north of the black shales and cherts, by the fewer number of felspar pebbles which they contain. They are more highly siliceous, the pebbles of quartz often reaching a considerable size. In thin sections these pebbles and grains of quartz, seen under the microscope, show evidence of having been subjected to considerable crushing by earth movement. Associated with these grits are beds of black or pale grey-coloured shales. Everywhere this zone of grits and shales shows evidence of being interstratified with the black shales and cherts which lie immediately to the north. Taken together, they form a well-marked group lying below the Leny grit, into which, so far as we have been able to see, they pass conformably.

To the south of the sedimentary series just described there comes a broad band of hornblende-schist, which stretches from Gualann Hill on the west to near the Drum of Clashmore on the east. Besides hornblende and felspar, this rock contains a large quantity of epidote. It appears to have been intruded into the grit at a period prior to its folding and crushing, and has been subjected to the same dynamic metamorphism as the sedimentary rocks. The hornblende-schist i

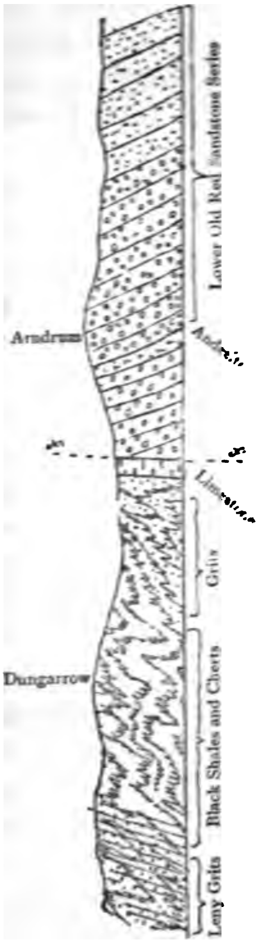


Fig. 59. Section across the Rocks of the Marginal Belt.

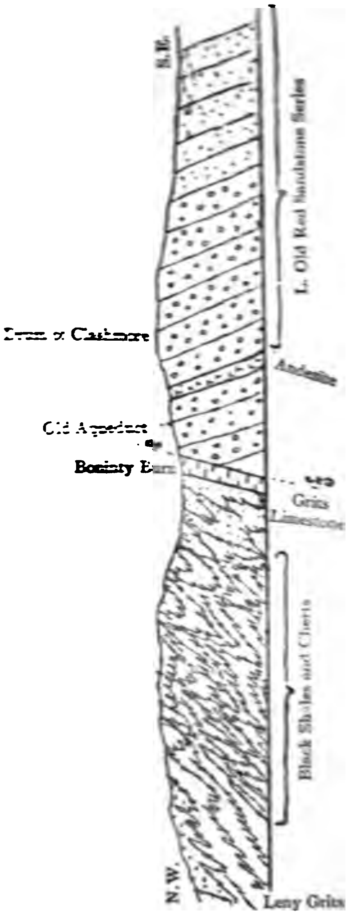


Fig. 60. Section across the Rocks of the Marginal Belt.

seen in many places to be distinctly foliated, and the foliation planes also show evidence of having been folded by a still later movement than that which produced the foliation. Contact metamorphism can also be observed in the sedimentary rocks where they meet the hornblende-schist. It seems to us that the occurrence of this bed of hornblende-schist in association with the sedimentary rocks just described goes to show that the whole group has been subjected to considerable metamorphism, and further bears out our contention that, taken as a whole, the beds cannot be considered as less highly altered than those which lie immediately to the north-west, and which are admitted to form an undoubted part of the Highland series (see sections across these rocks, Figs. 59 and 60).

The black shales, cherts, and grits which occur in Arran, and which are evidently the western extension of the Kelty series, are associated in that district with massive and schistose igneous rocks. Some of these show scoriaceous and vesicular structures, and are accompanied by such fragmental volcanic rocks as tuffs and agglomerates, so that they appear to be of the nature of contemporaneous lava flows. These rocks are, however, entirely absent in the Perthshire series, the hornblende-schist, already described, being most probably of the nature of an intrusive sill.

We have already pointed out that in Arran these rocks dip to the E.S.E. at high angles, and appear to overlie the crystalline-schists of the interior. It seems to us that, like the slates and grits which lie further to the north, they are inverted at this point by being brought into the margin of the great fan-

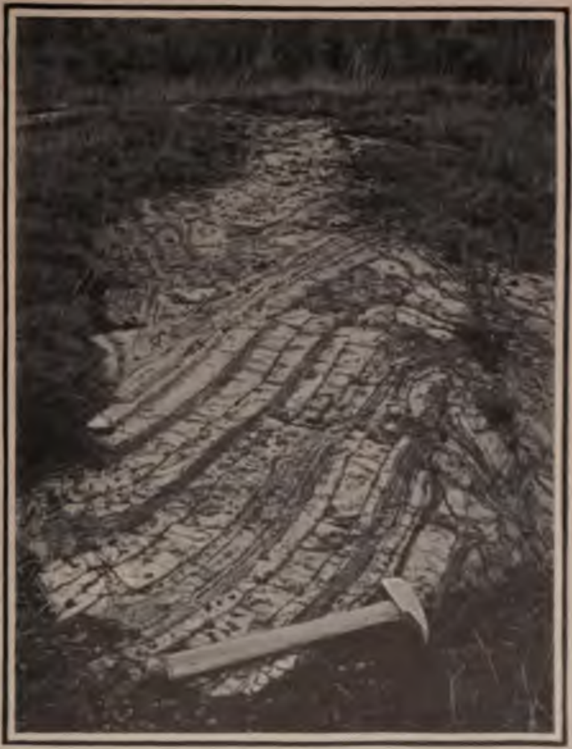


FIG. 61.—Folded Cherts in the Corrie Burn, West of Aberfoyle.

Photo. by S. FINGLAND.

shaped structure that formerly rose over what is now the Midland Valley.

As regards the relationships of the Perthshire rocks to those seen further to the N.E. in Forfarshire, which have been described by Mr. Barrow, the features do not appear to be exactly the same in both areas. Some have sought to recognize in the cherts and limestones of the Leny quarries the equivalents of Mr. G. Barrow's Margie group, but this cannot be looked upon as having been definitely settled.

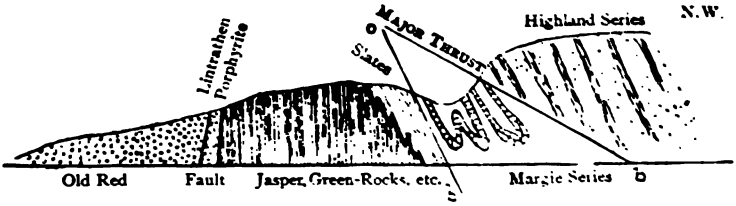


FIG. 62.—Section across the Marginal Belt in Kincardineshire. (After Barrow.)

According to Mr. G. Barrow, these rocks can be separated in Forfarshire and Kincardineshire into two divisions—the Jasper and Green-Rock Series, and the Margie Series. Both of these groups have been much deformed, and have suffered intense shearing along their junction with the Highland rocks. He further maintains that the apparent upward passage of these rocks into the Highland schists is entirely deceptive, they being everywhere separated from the schists by an overthrust, which he has traced for many miles. The accompanying section will help to explain the relationships of these rocks to the Highland schists as made out by Mr. Barrow (see Fig. 62).

As we have repeatedly pointed out, we cannot find any such line of demarcation in the rocks of the Aberfoyle district. Here they appear to form an integral part of the Highland series, along with which they have been folded.

To the east and west of Aberfoyle, and between the Old Red Sandstone rocks on the south and the black shales and cherts on the north, there occurs a belt of serpentinous and jaspery rocks, which may be conveniently referred to at this point. According to Mr. Du Toit,[1] the serpentinous belt consists of igneous, pyroclastic, and sedimentary materials, that have been much altered by dolomitization and silicification. The igneous rocks contain, or originally did contain, an orthorhombic pyroxene (either enstatite or bronzite), an orthorhombic amphibole (gedrite), diallage, and olivine. They are also characterized by having an abnormally large amount of alumina.

At Maol Ruadh a coarse-grained gabbro is seen to pass in places into a massive serpentine, which is often highly sheared and contains pebbles of grit, derived from the Highland series. Traced further west the serpentine passes into a talc-dolomite-serpentine rock, containing a large percentage of dolomite. By an increase of carbonate a ferriferous limestone is produced.

Mr. Du Toit thinks that the serpentine and gabbro must originally have formed part of a plutonic complex of basic igneous rocks, of considerable size, as they show evidence of having produced a considerable amount of contact metamorphism upon the grits and hornblende-schist into which they were erupted. That

---

[1] "The Lower Old Red Sandstone Rocks of the Balmaha-Aberfoyle Region," by Alex. L. Du Toit, B.A., F.G.S. *Trans. Edin. Geol. Soc.* vol. viii. p. 315.

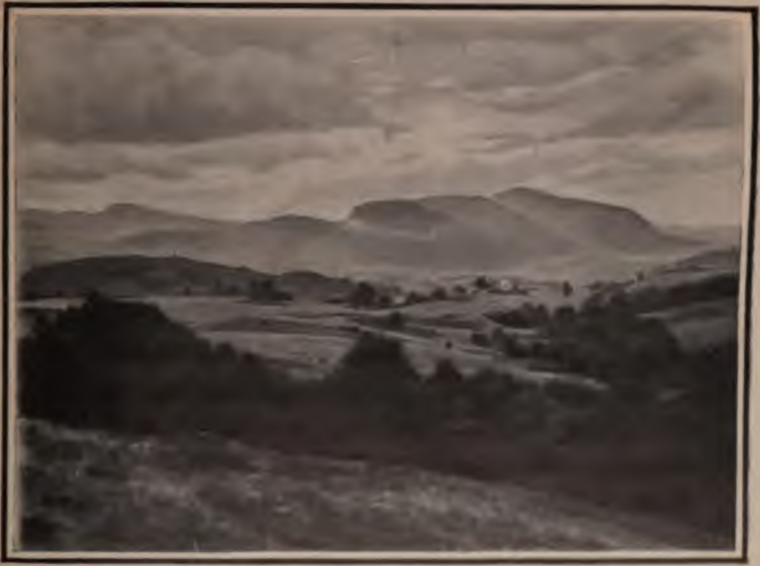


FIG. 63.—The Menteith Hills, from the West of Aberfoyle.

Photo. by S. FINGLAND.

they are older than the Old Red Sandstone seems to be proved by the absence of any signs of contact metamorphism in these rocks.

A similar series of changes can be seen to have taken place in the jasper belt. The serpentine can be traced into a sheared and highly altered rock in which carbonates and silicates of lime and magnesia predominate. This graduates into a foliated ferruginous limestone or dolomite. The next step in the process of alteration has been the replacement of the calcareous matter by silica, thus causing the rock to pass into a massive red jasper. It seems not unlikely that the silica which replaced the carbonates may have come up along the line of fault, held in solution in ferruginous water. The adjoining Old Red Sandstones and shales have been affected by it, so that it is often difficult to say where the jasper rocks terminate and the sedimentary rocks begin.

END OF VOL. I.

GLASGOW: PRINTED AT THE UNIVERSITY PRESS BY ROBERT MACLEHOSE AND CO. LTD.

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS.

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS.

AUG 19 1936